The Assessment of Aquatic Effects of Mining in Canada:

AQUAMIN

Supporting Document I

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Table of Contents

Page

1 Geology and Ore Deposits of Canada 1

1.1 Introduction 1

1.2 The Canadian Shield 1

1.2.1 The Archaean Eon (3.8 to 2.4 billion years ago) 4

1.2.2 The Proterozoic Eon (2.4 to 0.57 billion years ago) 5

1.3 The Appalachian Region 6

1.4 The Western Cordillera 7

1.5 Pleistocene Glaciation 8

1.6 Ore Deposits of Canada 9

1.7 Environmental Geochemistry 13

1.7.1 Acid Rock Drainage 13

1.7.2 Naturla Metal Occurrences in the Environment 17

1.7.3 Metal Speciation 18

1.7.4 Influence of Glaciation 21

2 Metal Mining and Milling Processes in Canada 23

2.1 Advanced Exploration and Mine Development 23

2.2 Mine Operation 25

2.3 Ore Processing 28

2.3.1 Comminution 28

2.3.2 Crushing 29

2.3.3 Grinding 29

2.3.4 Separation 30

2.3.4.1 Physical Separation Processes 30

2.3.4.2 Chemical Separation Processes 34

2.3.4.3 Reagent Consumption During Ore Processing . . 37

2.3.5 Dewatering 39

2.4 Environmental Managment During Mining and Ore Processing 40

2.4.1 Contaminants Due to the Deposit Mineralogy 40

2.4.2 Loss of Chemicals to Effluent 42

2.4.3 Wastewater Treatment Technologies 45

2.5 Mine Closure 51

3 The Regulatory Regime . . . 52
- 3.1 Development and Implementation of the MMLER . . . 52
  - 3.1.1 The *Fisheries Act* . . . 52
  - 3.1.2 Regulatory Approach . . . 53
  - 3.1.3 *Metal Mining Liquid Effluent Regulations* . . . 53
  - 3.1.4 Metal Mining Liquid Effluent Guidelines . . . 55
  - 3.1.5 Guidelines for Acute Lethality Measurement . . . 55
  - 3.1.6 Consideration of Gold Mine and Mill Effluents . . . 56
  - 3.1.7 The *Fisheries Act* and the *Canadian Environmental Protection Act* . . . 56
  - 3.1.8 Industry's Compliance Performance . . . 57
- 3.2 Effluent Regulatory Limits in other Jurisdictions . . . 59
  - 3.2.1 Domestic . . . 59
  - 3.2.2 International Effluent Limits . . . 63

Glossary . . . 68

References . . . 84

Appendix 1: Flowsheets for Mineral Separation Processes . . . 87

Appendix 2: Reagent Consumption at Canadian Metal Mines . . . 93

Appendix 3: Flowsheets for Effluent Treatment Technology Trains . . . 97

1 Geology and Ore Deposits of Canada

1.1 Introduction

This section provides a brief overview of the geology of Canada, with emphasis on areas where metal mining occurs in Canada. There are many ore deposit types that occur in Canada, and an overview of and table classifying these deposit types are included. Glaciation, and the effects of glaciation on ore deposits are also discussed briefly. In addition, the section provides a brief introduction to the principles of environmental geochemistry. Definitions of unfamiliar terms can be found in the glossary.

Canada is divided into nine geological regions (Figure 1). Most of Canada's known ore deposits occur in three of these regions: the Canadian Shield, the Appalachian Region, and the Western Cordillera. One ore deposit occurs in the sedimentary rocks of the Interior Platform, and two ore deposits occur in the sedimentary rocks of the Arctic Platform. This Section will focus on the Canadian Shield, the Appalachian Region, and the Western Cordillera.

1.2 The Canadian Shield

The Canadian Shield is a complex geological feature that covers about half of Canada including part of Newfoundland, Quebec, Ontario, Manitoba, Saskatchewan, and the Northwest Territories. The Canadian Shield represents the exposed portion of a larger feature known as the North American Shield which underlies much of North America, extending from Texas to the Arctic, and from British Columbia to Greenland. This section summarizes information from Hoffman (1989) and focuses on exposed rocks of the Canadian Shield.

The rocks of the Canadian Shield are of **Precambrian** age, formed over a time that covers about 90 per cent of the earth's history. The Precambrian is divided into two periods of time, the **Archaean Eon** which extends from 3.8 to 2.4 billion years ago, and the **Proterozoic Eon**, which extends from 2.5 to 0.57 billion, or 570 million years ago (see Table 1).

The Canadian Shield consists of eight geological provinces: **Hearne**, **Rae**, **Burwell** (formerly grouped as Churchill Province), **Superior**, **Slave**, and **Nain**, composed primarily of rocks of Archaean age, and **Bear** and **Grenville** Provinces, composed of rocks of Proterozoic age. Each of these provinces represents a former microcontinent whose borders are marked by eroded mountain, or orogenic, belts.

Figure 1: Geological regions of Canada

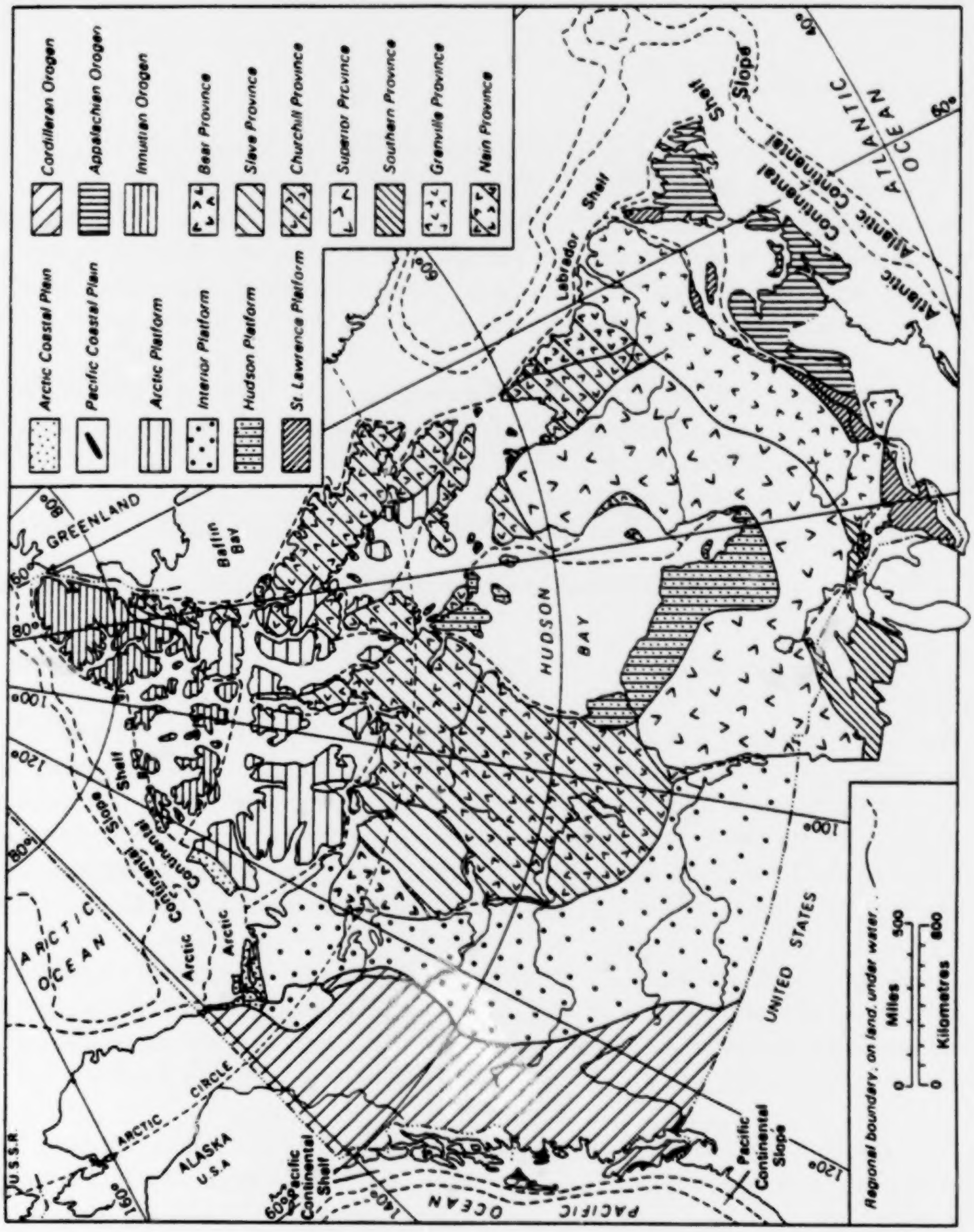

Arctic Coastal Plain
Pacific Coastal Plain
Arctic Platform
Interior Platform
Hudson Platform
St. Lawrence Platform
Cordilleran Orogen
Appalachian Orogen
Innuitian Orogen
Bear Province
Slave Province
Churchill Province
Superior Province
Southern Province
Grenville Province
Nain Province
GREENLAND
Baffin Bay
HUDSON BAY
Labrador Shelf
Shelf
Slope
Atlantic Continental Shelf
Atlantic Continental Slope
ATLANTIC OCEAN
ARCTIC OCEAN
Arctic Continental Shelf
Arctic Continental Slope
U.S.S.R.
ALASKA U.S.A.
ARCTIC CIRCLE
Pacific Continental Shelf
Pacific Continental Slope
PACIFIC OCEAN
UNITED STATES
Regional boundary, on land, under water
Miles 0 500
Kilometres 0 800
60°
80°
100°
120°
140°
160°

Table 1: The geological time scale

The age of rocks found in Canada covers a tremendous range, from among the oldest rocks in the world, to recent glacial deposits. The geological time scale gives the names and estimated ages of the various eons, eras and periods of geologic time which have been identified by geologists. The scale also gives the characteristic life forms which existed during each period. Note that the Proterozoic and Archaean Eons are commonly referred to collectively as the **Precambrian**.

Eon	Era	Period	Characteristic Life	Estimated time (million years)
Phanerozoic	Cenozoic	Recent Pleistocene	Humans	present - 1.5
		Pliocene Miocene Oligocene Eocene Palaeocene	Mammals and Modern Plants	1.5 - 65
	Mesozoic	Cretaceous Jurassic Triassic	Reptiles	65 - 225
	Paleozoic	Permian Carboniferous	Amphibians	225 - 570
		Devonian Silurian	Fishes	
		Ordovician Cambrian	Higher Invertebrates	
Proterozoic	Hadrynian		Algae, Lower Invertebrates	570 - 880
	Helikian			880 - 1,640
	Aphebian			1,640 - 2,390
Archaean				2,390 -4,500 or more

1.2.1 The Archaean Eon (3.8 to 2.4 billion years ago)

During the Archaean Eon the earth's crust was thin and there were few landmasses. Those landmasses that did exist were small and very mobile in a plate tectonic sense. The oldest parts of the Canadian Shield, the Archaean rocks of Hearne, Rae, Burwell, Superior, Slave, and Nain Provinces, are the remnants of these Archaean landmasses. The largest of these provinces is Superior Province, with an exposed area of 1.6 million km^2. While most of its rocks were formed between 2.8 and 2.7 billion years ago, some rocks in the province are more than 3.5 billion years old.

The provinces of the Canadian Shield formed by the successive accretion of smaller cratons and bodies of sedimentary and volcanic rock from the sea floor. As these portions of continental and oceanic crust accreted there was folding and uplift of the rocks, and intrusive igneous activity. As folding proceeded deep crustal rock was strongly metamorphosed as a result of high temperatures and pressures at depth. Rock closer to the surface was not as strongly metamorphosed. Thus, Superior Province and the other Archaean provinces are composed of roughly parallel belts of high grade metamorphic rocks, known as gneisses, metamorphosed intrusive igneous rocks, and areas of lower grade metamorphic rock. Areas of lower grade metamorphic rock derived from oceanic crust are commonly termed greenstone belts. Greenstone belts are composed primarily of mafic (Fe - Mg rich) and felsic (Si rich) volcanic rocks extruded onto the sea floor, and deep and shallow marine sedimentary rocks derived from submarine volcanic activity and continental erosion.

Archaean gneisses host few metallic mineral deposits, but greenstone belts are very important since many ore deposits of the Canadian Shield occur in them (see Section 1.6). In greenstone belts sulphide rich mineral deposits are commonly associated with the volcanics, and may also be associated with sediments, particularly those derived from submarine volcanic activity. The large concentrations of sulphide-rich deposits in greenstone belts may be related partially to the inference that the primary component in the earth's early atmosphere was sulphur. The atmosphere became oxygen-rich late in the Archaean, approximately 2.1 billion years ago.

The most productive of the greenstone belts is the Abitibi Greenstone Belt, located in northeastern Ontario and western Quebec. The precious metal and base metal mines of Timmins, Kirkland Lake, Larder Lake, and Matachewan in Ontario, and Rouyn, Noranda, Val D'Or, Malartic, Matagami and Chibougamau in Quebec, and the iron mines of Temagami and Kirkland Lake are included within this belt. Other mines, such as the gold mines of Red Lake and Geraldton in Ontario, Yellowknife and Contwoyto Lake in the Northwest Territories, and the base metal mines of Thompson, Manitoba, and Sturgeon Lake, Shebandowan and Manitouwadge in Ontario also occur in Archaean Greenstone Belts.

1.2.2 The Proterozoic Eon (2.4 to 0.57 billion years ago)

In the early Proterozoic, 2.4 to 2.0 billion years ago, the Archaean cratons were discrete, relatively stable units. Along the continental shelves of some of these cratons iron derived from submarine volcanic activity or continental erosion precipitated with silica and oxygen to form extensive iron rich sedimentary layers, known as iron formations.

During a series of orogenic events 2.0 to 1.8 billion years ago these smaller cratons accreted into the much larger proto-North American craton. During this series of orogens Superior and Rae Provinces collided, forming an orogenic belt near the current Quebec-Labrador border. As this belt was formed iron formations on the continental shelf off the coast of the craton forming Superior Province were thrusted and folded into belts. These iron formations are the major source of iron in Canada, with much of the mining activity concentrated near the Quebec-Labrador border in Schefferville, Labrador City, Wabush and Mount Wright. Similar iron formations exist along the east coast of Hudson Bay on the Nastoroka and Belcher Islands.

In the mid Proterozoic, 1.3 to 1.0 billion years ago, the last major orogenic event in the formation of the Canadian Shield, the Grenvillian Orogeny, occurred. This event was preceded by deposition of continental shelf sediments along the east coast of the craton. The Grenvillian Orogeny folded these sediments, and material from Superior Province, into a mountain chain. As a new continental shelf formed deposition resumed in the ocean, known as the Iapetus, which then separated North America and Europe.

Precious metal mining has not been as prolific in Proterozoic rocks as in Archaean rocks of the Canadian Shield, but base metal and ferrous metal mining in Proterozoic rocks has been extensive. In addition to the iron mines of Quebec and Labrador, there are several base metal mines in northern Manitoba in an orogenic belt between Superior Province and Hearne Province. Productive mines are found in Flin Flon, Snow Lake and Lynn Lake Manitoba. This orogenic belt, and a second belt between Hearne and Rae Provinces host uranium deposits in Saskatchewan.

Within Superior Province are three important mineral producing areas of Proterozoic age: 1) the uranium mines of Elliot Lake, Ontario, formed as a result of Proterozoic sedimentary activity; 2) the base metal mines of Sudbury, Ontario, formed as a result of intrusive igneous activity during the Proterozoic; and 3) the silver mines of Cobalt, Ontario, also formed as a result of Proterozoic intrusive igneous activity.

1.3 The Appalachian Region

The Appalachian Region is an area of partially eroded mountains formed during the Palaeozoic Era. Remnants of these mountains occur in Newfoundland, Prince Edward Island, Nova Scotia, New Brunswick, and in Quebec south of the St. Lawrence River. Appalachian bedrock is primarily sedimentary, but includes some intrusive and extrusive igneous rocks. Information for this section is drawn from Stanley (1986).

In the late Proterozoic and the Cambrian Period, sediments produced by erosion of the Canadian Shield were deposited in the Iapetus Ocean. During the Cambrian and early Ordovician there was extensive deposition of limestone in the warm shallow waters of the Iapetus.

In the mid Ordovician, the Taconian orogeny occurred. During this orogeny oceanic crust of the Iapetus Ocean descended under the continental crust of North America, resulting in uplift and folding of continental and oceanic rocks, and the emplacement of intrusive igneous bodies within the new mountain belt. As the Iapetus Ocean closed North America and northern Europe moved closer together, and they may have collided late in the Taconian.

During the Silurian Period the mountains were levelled by erosion. North America and Europe moved apart, and sediments from this erosion were deposited in the Iapetus Ocean. In the Devonian Period the Acadian orogeny occurred as a result of another collision of North America and northern Europe. As the two land masses approached, sections of oceanic crust, including volcanic rocks, were thrust onto the continental masses. These rocks formed by submarine volcanic activity similar to that which led to the formation of Archaean Greenstone Belts. These bodies of oceanic crust host important ore deposits in Newfoundland (Buchans, Baie Verte), New Brunswick (Brunswick Mining and Smelting in Bathurst and Heath Steele Mines in Newcastle), and Quebec (Solbec Cupra and other copper mines of the Eastern Townships).

At the end of the Acadian orogeny, North America and northern Europe formed a single continent. South of this continent was a second large continent composed of South America, Africa, the Middle East, and India. In the late Carboniferous Period, these two continents collided, forming a single continent. This resulted in a further period of mountain building known as the Alleghenian orogeny. This was the last major period of formation of rocks in the Appalachian Region. After the end of the Alleghenian orogeny, erosion again levelled the mountains. During the Mesozoic Era Europe and North America began to move apart and the North Atlantic Ocean began to open.

1.4 The Western Cordillera

The Western Cordillera is part of a larger tectonic unit in western Canada known as the Cordilleran Orogen. This is an area of mountain ranges and high plateaus in western Alberta, British Columbia, the western Northwest Territories, and the Yukon Territory. The Rocky Mountains of western Alberta and eastern British Columbia, and several smaller mountain ranges in the Northwest Territories comprise the Eastern Cordillera, an important source of oil, natural gas, coal, and industrial minerals. To date, metal production from the Eastern Cordillera has been limited. The Western Cordillera comprises the interior mountain ranges and plateaus of British Columbia, the coastal ranges, and several mountain ranges in the Yukon, including the St. Elias Mountains. The Western Cordillera is host of many important base metal and precious metal deposits.

The economic geology of the Eastern and Western Cordilleras is quite different, but their history is very closely related. Thus, this section summarizes the history of the Cordilleran Orogen as a whole. Information for this section is drawn from Stanley (1986).

Throughout the late Proterozoic and the Palaeozoic, the west coast of North America was a stable area of marine deposition of sedimentary rocks. In the mid Triassic Period the first major phase of Cordilleran mountain building occurred. At this time, oceanic crust of the Pacific Ocean began to move under continental crust along the entire Pacific margin of the Americas, from Alaska to Chile. This activity resulted in folding and thrusting of sedimentary rocks, and the emplacement of intrusive and extrusive igneous rocks. The resultant mountain chain was much like the modern Andes in Chile, which are being formed by the same processes.

During the Jurassic Period a small cratonic body, carried by the oceanic crust of the Pacific Ocean, collided with the western margin of Canada, and was joined to the continent. This resulted in extensive folding and thrusting of sedimentary rocks along the western margin of Canada, in the area of the modern Rocky Mountains. In the Cretaceous Period, a second small cratonic body collided with western Canada. This collision resulted in further folding and thrusting, and resulted in extensive igneous activity along the margin between the two cratonic bodies. This process of continental accretion was much like that which resulted in the formation of large late Archaean cratons.

In the Tertiary Era the Laramide Orogeny, the final event in the formation of the Cordilleran Orogen, occurred. This orogeny featured extensive igneous activity near the coast, and active folding and thrusting further inland. Structures formed during the Laramide are well exposed in many parts of the Rocky Mountains.

Erosion rates during the Laramide Orogeny were very high, and soon after the orogeny all that remained was a high plateau interrupted by a few low hills. The modern mountains were formed as a result of uplift and subsequent erosion in much more recent times.

Many ore deposits of the Western Cordillera were formed as a result of the igneous activity that occurred during the various orogenic events. In particular, this activity was instrumental in the formation of precious metal, base metal, tungsten and tin deposits mined at such sites as Island Copper, Highland Valley, Granisle, Endako, Mount Washington, Craigmont and Coast Copper in British Columbia, and Tungsten in the Northwest Territories.

1.5 Pleistocene Glaciation

The last major geological event to affect Canada was the Pleistocene glaciation. This recent geological event influences mineral exploration and mining in ways that are unique to Canada and northern Europe among major mineral producing countries of the world. Information for this section is drawn from Fulton (1989).

At least 95% of the Canadian landmass has been glaciated at some time during the last million years. Most (>90%) of the country was traversed by glaciers of the last period of glaciation, the Wisconsinan, which reached its maximum development about 18000 years ago. The Wisconsinan ice complex comprised two major continental centres in Labrador/Nouveau Quebec and the District of Keewatin in the Northwest Territories. Ice from these centres coalesced in the Hudson Bay depression forming a continental ice sheet which spread south, east and west. As it spread, this ice sheet coalesced with maritime and highland ice sheets in the Cordillera, the Arctic islands, Baffin Island, Newfoundland and the Atlantic Provinces.

These ice sheets, up to 2 km thick, were powerful agents of erosion. As the ice sheets advanced, they swept away most of the preglacial soils and cut into fresh bedrock, removing from one to several metres of rock. Entrained in the ice, or ground along the underlying rock surface, the eroded rock was further crushed into boulders, sand, silt and clay. This material was transported varying distances down ice. Some material was deposited under the moving ice, but most was deposited on the ground surface as a heterogenous layer at the head of the glacier as the glacier melted. By moving rock debris down ice from its original location, glaciation has distorted the surficial compositional signature of the underlying bedrock in many regions of Canada.

The upper 1 to 3 m of this glacial sediment, known as glacial till, has had only 6000 to 12000 years to equilibrate chemically with the atmosphere, as compared to millions of years for soils in unglaciated areas. As a result, the glacial till retains many chemically active mineral phases, such as sulphide minerals. Deep glacial sediments that have not been oxidized or leached contain all of the reactive components released from the crushing of unweathered bedrock by glacial action. Down ice from mineral deposits the glacial till may contain ore material and host rock in a wide range of size fractions. Thus, glacial sediments, which cover much of Canada, may have many of the mineralogical and chemical characteristics of mine tailings or waste rocks, particularly in areas down ice from mineral deposits.

1.6 Ore Deposits of Canada

There is a wide range of ore deposit types in many different geological environments in Canada. The modes of formation and characteristics of these deposit types are summarized in Table 2. Information for this table is drawn from Eckstrand (1984) and Guilbert and Park (1986). In this table, deposits are classified as follows (after Guilbert and Park 1986):

1) Ore deposits related to intrusive igneous activity
   A) mafic intrusives
   B) intermediate to felsic intrusives

2) Ore deposits related to submarine volcanic activity

3) Ore deposits related to subaerial volcanic activity

4) Ore deposits related to solution-remobilisation

5) Ore deposits of doubtful igneous connection

6) Ore deposits related to sedimentary processes

Table 2: Major base metal, precious metal and uranium ore deposit types of Canada

Deposit Type	Commodities • primary • secondary	Examples	Ore Minerals	Associated Minerals
1A) Deposits Related to Intrusive Igneous Activity: Ultramafic to Mafic Intrusives				
Deposits form as a result of the intrusion into continental crust of iron and magnesium rich magma. Differentiation of the magma occurs, resulting in the formation of layers within the intrusive body. Each layer has a characteristic mineral composition, and ore minerals may be associated with particular layers. Within ore bearing layers, metallic minerals (sulphides and/or oxides) are massive, that is, the rock is composed primarily of metallic minerals.				
Ultramafic associated nickel, copper	• Ni, Cu • Pt, Pd, Co	• Langmuir, Marbridge & Shebandowan, ON • Mines of Thompson, MN • Deposits of the Ungava region, PQ	• **sulphides:** bornite, pentlandite, millerite, chalcopyrite • Platinum group minerals	• **sulphides:** pyrrhotite, pyrite • **oxides:** magnetite, chromite • **silicates**
Gabbro associated nickel, copper	• Ni, Cu, platinum group metals • Co, Au, Ag, Fe	• Mines of Sudbury, ON • Great Lakes Nickel, ON • Lynn Lake, MN • Giant Mascot, BC • St. Stephen, NB	• **sulphides:** pentlandite, chalcopyrite, cubanite, millerite • Platinum group minerals • native gold & silver	• **sulphides:** pyrrhotite, pyrite, sphalerite, millerite • **silicates**
1B) Deposits Related to Intrusive Igneous Activity: Intermediate to Felsic Intrusives				
Deposits form during periods of orogenic activity, as a result of the intrusion of igneous bodies of intermediate to felsic composition. Deposits are layered as a result of different temperatures in the intrusive rocks and host rocks during the intrusive event. As a result, different ore minerals may occur at varying distances from the centre of the intrusion. Ore minerals are disseminated through the host rocks, that is, occur are relatively small concentrations. For example, in porphyry copper deposits, the copper concentration is typically below 1%. These deposits can be very large, up to 1 to 2 km^2 in outcrop area.				
Porphyry copper, molybdenum, tungsten	• Cu, Mo, W • Au, Ag, Sn, Bi	• Island Copper, Highland Valley, Brenda, Granisle, Galore Creek, Endako, Alice Arm, Adanac, Mt. Washington & Mt. Polley, BC. • Logtung & Red Mountain, YT • Mt. Pleasant in NB	• **sulphides:** chalcopyrite, bornite, chalcocite, enargite, molybdenite • **tungstates:** scheelite, wolframite, • **oxide:** cassiterite	• **sulphides:** pyrite & other sulphides • **oxide:** magnetite • **silicates** • **carbonate:** calcite
Skarn copper	• Cu • Fe, Au, Ag, Mo	• Craigmont, Phoenix, Ingerbelle and Coast Copper, BC • Whitehorse Copper, YT • Mines Gaspé & Madeleine Mines, PQ	• **sulphides:** chalcopyrite, bornite, molybdenite • **oxide:** magnetite	• **sulphides:** pyrite, pyrrhotite • **oxide:** hematite • **carbonates:** calcite, dolomite • **silicates**
Vein copper gold	• Cu • Au, Ag	• Opemiska & Chibougamau Districts, Icon area, PQ • Bruce Mines, ON • Churchill, BC • Dublin Gulch, YT	• native gold • **sulphides:** chalcopyrite, bornite, chalcocite	• **sulphides:** pyrite, pyrrhotite • **oxides:** hematite, magnetite • **silicates** • **carbonates**

Table 2 (continued)

Deposit Type	Commodities • primary • secondary	Examples	Ore Minerals	Associated Minerals
2) Deposits Related to Submarine Volcanic Activity				
Deposits form on the sea floor, as a result of volcanic activity in areas where new oceanic crust is being formed. Minerals are precipitated from solution in rocks below the ocean floor, or these superheated solutions may be vented to the ocean water. When this occurs, minerals are precipitated in the water column, and are deposited on the sea floor. Metallic minerals occur in massive form.				
Volcanogenic Massive Sulphides	• Cu, Zn, Ag, Au • Pb Cd, Sn, Sb, Bi, Ba	• Flin Flon, MN • Kidd Creek Mine,Timmins, ON • Millenbach & Home Mines near Noranda, PQ • Buchans, & Betts Cove, NF • Brunswick No. 12, Bathurst, NB • Western Mines, BC	• **sulphides:** galena, sphalerite, chalcopyrite • native gold & silver	• **sulphides:** pyrite, pyrrhotite, bornite • **oxides:** magnetite, hematite • **sulphate:** gypsum • **silicates** • some **carbonates**
Sediment Hosted Sulphides	• Zn, Pb, Ag, Ba • Cd, Cu, Sn	• Sullivan Mine, BC • Faro, Howards Pass, Tom & Jason deposits, YT	• **sulphides:** galena, sphalerite • **sulphate:** barite	• **sulphides:** pyrite, pyrrhotite, marcasite, chalcopyrite, arsenopyrite • **oxide:** cassiterite • **silicates**
Chemical Sediment Hosted Gold	• Au • Ag, Cu	• Detour Lake, Geraldton, Pickel Crow, ON • Lupin Mine, NWT • Several mines in the Noranda area, PQ	• native gold	• **sulphides:** pyrite, arsenopyrite, pyrrhotite • **oxides:** magnetite, hematite • **silicates** • **carbonates**
3) Deposits Related to Subaerial Volcanism				
Deposits formed as a result of volcanic activity at the earth's surface. Commonly formed as a result of the dissolution of metals by superheated groundwater, and the subsequent deposition of the metals at or near the earth's surface as the groundwater cools				
Epithermal Silver-Gold	• Ag, Au • Cu	• Blackdome, Lawyers, Iskut River in BC • Mt Skukum, YT	• native gold & silver	

Table 2 (continued)

Deposit Type	**Commo-dities** • **primary** • **secondary**	**Examples**	**Ore Minerals**	**Associated Minerals**
4) Deposits Related to Solution-remobilisation				
Deposits formed during an intrusive igneous event. As the magma intrudes the host rock, superheated fluids dissolve metals in the rock. The metal rich solutions later cool in fractures in the rock, resulting in the precipitation of ore minerals in the host rock adjacent to the intrusion, and sometimes, in the intrusion itself.				
Intrusive associated gold	• Au • Ag	• Mines in Val d'Or & Malartic, PQ • Wilmat mine in Red Lake, Schumacher & Hollinger mines, Timmins, & mines in Kirkland Lake, ON	• native gold	• **sulphides:** pyrite, and sometimes other sulphides • **carbonates** • **silicates**
Volcanic associated vein gold	• Au • Ag	• Con & Giant Mines, NWT • Dome & Pamour Mines in Timmins, Campbell Mine in Red Lake, Kerr Addison Mine in Virginiatown, ON	• native gold	• **sulphides:** pyrite, arsenopyrite, minor sulphides • **silicates** • **carbonates**
Arsenide vein silver, uranium	• Ag, U • As, Co, Ni, Cu, Bi	• silver mines in Cobalt, ON • silver, uranium mines of the Great Bear Lake District, NWT	• native silver • **oxide:** uraninite • **sulphides and sulpharsenides**	• **arsenides and sulpharsenides** • **carbonates** • **silicates**
Intrusion Associated Silver Lead Zinc Veins	• Ag, Pb, Zn • Cd, Au, Cu	• many small deposits in s.e. BC • Keno Hill Galena Hill District, YT	• native silver • **sulphides:** galena, sphalerite, Ag-sulphides	• **sulphides:** pyrite, chalcopyrite, arsenopyrite • **silicates** • **carbonates**
5) Deposits of Doubtful Igneous Relation				
Deposits may have been formed as a result of igneous activity. Mechanism of formation is unknown, so it is not clear whether igneous activity was involved.				
Unconformity Associated Uranium	• U • Ni, Co, As, Se, Ag, Au, Mo	• Key Lake, Rabbit Lake & Cluff Lake, SK	• **oxides:** uraninite & other U-oxides	• **arsenides and sulpharsenides** • **sulphides:** galena, Cu & Fe sulphides • **selenides** • **silicates** • **carbonates**
Mississippi Valley Lead Zinc	• Pb, Zn • Ag, Cd	• Pine Point & Polaris in NWT	• **sulphides:** galena, sphalerite	• **sulphides:** pyrite, marcasite • **carbonates:** calcite, dolomite • **silicates**

Table 2 (continued)

Deposit Type	**Commodities** • **primary** • **secondary**	**Examples**	**Ore Minerals**	**Associated Minerals**
6) Deposits Related to Physical Sedimentary Activity				
Deposits formed as a result of the erosion of mineral deposits, and the subsequent transportation and deposition of ore minerals in the sediments of streams, beaches, or continental shelves. In particular, sedimentary processes can concentrate minerals are high density, such as gold and uranium bearing minerals.				
Pyritic Paleoplacer	• U • Th, rare earth elements	• Elliot Lake, ON • Padlei, NWT • Sakami Lake, PQ	• **oxides:** uraninite, brannerite, uranothorite • **phosphate:** uranoan monazite	• **sulphide:** pyrite • **silicates** • **oxide:** rutile-anatase • **phosphate:** monazite

1.7 Environmental Geochemistry

1.7.1 Acid Rock Drainage

As is evident from Table 2, sulphide minerals are ore minerals for many base metals, and are almost ubiquitous in their occurrence in ore deposits. In addition, sulphides, particularly pyrite, also occur commonly in host rock for ore deposits, and in country rock, away from any ore deposits. They can occur in a wide range of rock types, formed under a range of conditions.

Sulphides are minerals in which one or more metals are bonded to sulphur. For example, pyrite, a common sulphide mineral, has the chemical formula FeS_2. Sulphides, in addition to being important ore minerals, are also important from an environmental perspective, because in the presence of water and oxygen, at or near the earth's surface, they can oxidize to generate sulphuric acid. This is called **acid rock drainage (ARD)**. It can occur as a result of natural process, or as a result of human activity such as mining or construction. In the context of mining, this process is frequently called **acid mine drainage (AMD)**. This section is adapted from Mills (1995).

Basic Chemistry of Acid Rock Drainage Generation

The following chemical reactions describe the oxidation of pyrite (FeS_2) to the products that constitute the contaminants generically termed Acid Rock Drainage (ARD). Similar equations may be written for the oxidation of other sulphides.

Equation 1	$FeS_2 + 7Fe_2(SO_4)_3 + 8H_2O \rightarrow 15FeSO_4 + 8H_2SO_4$
Equation 2	$FeS_2 + Fe_2(SO_4)_3 \rightarrow 3FeSO_4 + 2S$
Equation 3	$4FeSO_4 + O_2 + 2H_2SO_4 \xrightarrow{\text{bacteria}} 2Fe_2(SO_4)_3 + 2H_2O$
Equation 4	$2S + 3O_2 + 2H_2O \xrightarrow{\text{bacteria}} 2H_2SO_4$
Equation 5	$4FeS_2 + 15O_2 + 2H_2O \rightarrow 2Fe_2(SO_4)_3 + 2H_2SO_4$
Equation 6	$S + 3Fe_2(SO_4)_3 + 4H_2O \rightarrow 6FeSO_4 + 4H_2SO_4$

The formulae representations are:

- FeS_2 - pyrite
- H_2O - water
- O_2 - oxygen
- S - sulphur
- H_2SO_4 - sulphuric acid
- $FeSO_4$ - ferrous sulphate
- $Fe_2(SO_4)_3$ - ferric sulphate

Note that Equations 3 and 4 contain the term "bacteria" in addition to chemical formulae. The bacteria, which are usually site-specific strains of *Thiobacillus ferrooxidans*, utilize the sulphur present as their source of energy. They are autotrophic, obtaining their nutritional needs from the atmosphere (nitrogen, oxygen, carbon dioxide and water) and from minerals (sulphur and phosphorus). While these bacteria are not catalysts by true definition, they do act as accelerating agents if their habitat conditions are at or close to optimal and they are an important factor in the generation of ARD. They are also capable of adaptation by mutation if their habitat is markedly changed.

It is thought that in the absence of bacteria (usually *T. ferrooxidans*) Equations 1, 2 and 5 predominate, while in the presence of bacteria reactions are best described by Equation 5, which can be regarded as a combination of Equations 1 and 3, or 2, 3 and 4, or 1, 2, 3 and 4.

It may be seen that in addition to pyrite, the presence of both *oxygen* and *water* is required for process progression. This has important ramifications in that removal of the oxygen source (eg. by total submersion under water) or the water source (eg. conditions of aridity) will halt ARD production. Depending upon the availability of water and oxygen, reactions may not always approach completion as indicated by equations 1 to 6, and in such cases intermediate phases of chemical compounds or minerals may remain at the oxidation site. ARD production would also be considerably slowed or halted by the termination of *T. ferrooxidans* reproduction by a bactericidal agent.

The end products of ARD are sulphuric acid and ferric sulphate. Also, sulphuric acid is an important intermediate product. From the onset of pyrite oxidation, pH falls (acidity increases) quickly and then stabilizes, typically at values around pH 2.5 to 3.0. The pH of stabilization is normally determined by the optimal habitat requirement of the site-specific strain of bacteria.

If metallic minerals (such as galena [lead sulphide, PbS], chalcopyrite [iron-copper sulphide, $CuFeS_2$], or sphalerite [zinc sulphide, ZnS]) are present in addition to pyrite and pyrrhotite (as is usually the case in the natural oxidation of a mineral deposit and the oxidation of products from the mining of a mineral deposit) then there may be a secondary effect of the oxidation of the iron-sulphur minerals to sulphuric acid and ferric iron.

The stable pH developed (2.5 to 3.0) and the products of the sulphuric acid and ferric sulphate create conditions where the ferric iron ion itself can act as an oxidant (above about pH 3 the ferric ion is itself hydrolysed to ferric hydroxide, which precipitates as the familiar rust-coloured stain associated with ARD). In the absence of ferric iron at pH 2.5 to 3.0, sulphuric acid will dissolve some heavy metal carbonate and oxide minerals, but has little reactive effect on heavy metal sulphides. However, ferric iron ion is capable of dissolving many heavy metal sulphide minerals, including those of lead, copper, zinc, and cadmium, by the general reaction:

Equation 7 $$MS + nFe^{+++} \leftrightharpoons M^{n+} + S + nFe^{++}$$

Where:

- MS - solid heavy metal sulphide
- Fe^{+++} - aqueous ferric iron ion
- M^{n+} - aqueous heavy metal ion
- S - sulphur
- Fe^{++}-aqueous ferrous iron ion

Basic Acid Rock Drainage Kinetics

While chemical equations and their related thermodynamic data are a useful concept in the understanding of ARD generation, they refer to equilibrium conditions at infinite time and give no indication of the kinetics, or speed, with which a reaction will take place. The kinetics of chemical reactions are considered to be either chemically or transport controlled. A chemically controlled reaction is one controlled only by the concentrations of the chemicals reacting with one another, while a transport controlled reaction is dependent upon the rate of transfer of reagents or products to or from the reaction site. It is also reasonable to consider reaction rates controlled by biological activity to be a separate case.

ARD generation is a complex group of reactions which involve all three of these possibilities vying for dominance. Thus in conditions of atmospheric oxidation it is probable that ARD generation is predominantly transport controlled during periods of high rainfall and runoff, biologically controlled during low rainfall and optimal temperature for bacterial growth, and chemically controlled at other times. At any given time control may involve all three mechanisms.

In addition, temperature affects these three rate processes differently, and temperature effects are controlled not just by atmospheric variations but also by the heat generated by the (exothermic) chemical reactions and the rate of dissipation of this heat. Thus seasonal variations of precipitation may affect the transport characteristics of the process by water flow, and temperature control through heat transfer.

It follows that prediction of ARD generation rates is a complex, difficult process involving the interaction of a large number of system variables. The prediction of metal hydroxide precipitation from ARD is equally difficult because of the complexity of the reaction kinetics.

Neutralization of ARD

Carbonates are minerals in which one or more metals are bonded to the carbonate ion, CO_3^{-2}. The most common carbonate mineral is calcite, $CaCO_3$. Carbonates are relatively stable in the presence of oxygen and water, but in the presence of acids they are reactive. As a result, carbonate minerals can neutralize ARD. For example, when calcite is exposed to sulphuric acid generated during ARD, the acid is neutralized, and the reaction products are bicarbonate (H_2CO_3), sulphate (SO_4^{-2}) and calcium:

Equation 8 $CaCO_3 + H_2SO_4 \rightarrow Ca^{+2} + H_2CO_3 + SO_4^{-2}$

The bicarbonate ion may form a significant component in groundwater and buffer acidic waters when a mixing zone is encountered.

As neutralization occurs metallic ions such as Fe^{3+} and Cu^{2+}, Zn^{2+}, Pb^{2+} and As^{3+} will react to form hydroxides as precipitates by the general reaction:

Equation 9 $M^{n+} + nOH^{-} \rightarrow M(OH)_n \downarrow$

Where:

- OH^- - hydroxyl ion
- $M(OH)_n$ - metal hydroxide

This over-simplification represents chemical neutralization as it occurs by human intervention, rather than an accurate portrayal of natural occurrence, where the precipitation products are usually carbonates and sulphates and their hydrated and/or hydroxy-complex forms (as in Equation 8). In nature, acid generating minerals such as pyrite often occur in close association with acid neutralizing minerals such as calcite and dolomite, and acid produced from pyrite is neutralized, *in situ*, by these minerals.

Geologists determine both the acid producing and acid neutralizing mineral contents of samples from a proposed mine site and analyze the results by a method called Acid-Base Accounting (ABA). If the buffering capacity of the minerals in the deposit is exhausted before the acid generating capacity, then acidic drainage will occur. Conversely, if the buffering capacity is greater than the acid generating capacity, then acidic drainage will not occur.

Many ore deposit types in Canada, such as volcanogenic massive sulphide deposits (*e.g.* Kidd Creek, Horne and Brunswick No. 12 mines), have little or no buffering capacity. If these deposits are exposed at the surface, or if wastes from the mining of these deposits are exposed, acidic drainage may result. Mississippi Valley Lead Zinc deposits (*e.g.* Pine Point and Polaris mines) have a similar suite of sulphide ore minerals, but there is associated calcite in the limestone host rock. The buffering capacity in these deposits is high, and no acidic drainage occurs.

1.7.2 Natural Metal Occurrences in the Environment

Metals occur naturally in all environmental compartments, including soil, water, sediment, and plant and animal tissue. Natural concentrations of metals in the environment are dependant upon geological and biological interactions between rock, soil, water and vegetation. If the dominant source of the parent material is non-mineralized and unaltered, metal concentrations tend to be low. If the source is mineralized and/or altered, then higher metal concentrations can be expected. Mineralized areas include both metallic and non-metallic minerals. Metal levels in the vicinity of a particular site can be compared with levels determined through regional baseline studies. Anomalous concentrations may be several orders of magnitude higher than environmental quality guidelines values.

Metals are released to the environment primarily as a result of oxidation of metal-bearing minerals. Under oxidizing conditions, at a pH of 5 to 8, the relative mobility of metals is:

$$Mo > F - Zn - Ag - U - As - Hg > Mn - Pb - Cu - Ni - Co > Fe$$

Once released to the environment, metals can be: taken up by vegetation; moved by surface and ground waters; and/or mechanically dispersed.

As discussed in the next section, the biogeochemistry of metals in surface water is complex. Factors which affect metal concentrations in surface water include: local and upstream geology, type and extent of soil cover, physical and chemical characteristics of sediment, sediment loading, time of year, concentration of dissolved organic carbon, pH, oxidation/reduction potential, and temperature.

1.7.3 Metal Speciation

Metals in the environment can occur in various media as free ions, inorganic and organic complexes, colloids, absorbed on inorganic and organic material, precipitates or incorporated within biological materials. Speciation is complex and dependent on temperature, pH, dissolved oxygen, concentration and other factors. Examination of Eh - pH diagrams indicates the complexity of metal speciation (Garrels and Christ, 1965). Both total and dissolved metals must be taken into account because chemical species of a particular metal can have different impacts on aquatic organisms (i.e., bio-availability). Natural waters are multicomponent electrolyte solutions. A study by Williamson and Parnell (1994), demonstrates the use of selective, sequential extraction of metals from lake sediments and its implications for selective metal remobilization under variable environmental conditions, both natural and anthropogenic. This has a direct bearing on natural background metal concentrations.

To illustrate the complexity of speciation of a range of metals in the environment, the speciation of arsenic, copper, mercury and nickel is briefly described below.

Arsenic

Arsenic (As) is a metalloid element. Chemically, it behaves like both metals and nonmetals, particularly sulphur. It can exist in four different valencies: -III, 0, +III and +V, but in nature, only the +III and +V valencies are important. The primary inorganic forms of arsenic in the environment are sulphide, sulpharsenide and arsenide minerals, particularly realgar (AsS), orpiment (As_2S_3), arsenopyrite (FeAsS), cobaltite (CoAsS), and the skutterudite series ($(Co,Ni)As_{2-3}$)(Berry *et al.* 1983). In these minerals, arsenic occurs as As (+III). Under oxidizing conditions these minerals alter to secondary minerals such as scorodite ($FeAsO_4 \cdot 2H_2O$) which are slightly water soluble, and which can further alter to water soluble arsenates (Boyle and Dass 1971).

In sediments arsenic exists as dissolved species and it can be absorbed onto or coprecipitated with iron and manganese oxyhydroxides. It can also be fixed in clay minerals and organic matter

(Cullen and Reimer 1989).

In aerobic waters arsenate (AsO_4^{-3}) is the most common form of arsenic, but under anaerobic conditions, arsenite (AsO_3^{-3}) is the more common form. Under reducing conditions bacteria can methylate arsenic producing methyl-, dimethyl- or trimethylarsine gases (*e.g.* $(CH_3)_3As$), which are eventually oxidized to methylarsinic acid ($(CH_3)H_2AsO_3$), dimethylarsinic acid ($(CH_3)_2HAsO_2$) and trimethylarsine oxide ($(CH_3)_3AsO$) (Cullen and Reimer 1989).

Due to its complex chemistry arsenic transformations are common. Transformations can occur as a result of changes in pH, Eh, temperature and concentration, as well as biological activity. The ultimate sink for arsenic is ocean sediments.

Copper

Copper (Cu) occurs in three oxidation states, Cu(0), Cu(+I) and Cu(+II) (Aaseth and Norseth 1986). Copper occurs in a wide range of mineral deposit types, and as both primary and secondary minerals. Native copper does occur in nature, and historically, native copper deposits were very important (Berry *et al.* 1983). About 75% of modern copper production comes from sulphide ores. The most important copper-sulphide minerals are chalcopyrite ($CuFeS_2$), chalcocite (Cu_2S), bornite (Cu_5FeS_4) and tetrahedrite ($(Cu,Fe)_{12}Sb_4S_{13}$). Secondary copper minerals include the oxide mineral cuprite (Cu_2O), the carbonate minerals malachite ($Cu_2(CO_3)(OH)_2$) and azurite ($Cu_3(CO_3)_2(OH)_2$), and the sulphate minerals brochantite ($Cu_4SO_4(OH)_6$) and antlerite ($Cu_3SO_4(OH)_4$), all of which can be copper ore minerals, depending on their mode of occurrence and abundance (Berry *et al.* 1983).

The oxidation of copper-sulphide minerals will result in the release of Cu^{+2} to the environment. This ion tends to exist as a hydrated ion such as $Cu(H_2O)_6^{+2}$ (Flemming and Trevors 1989). Copper ions in solution can be complexed, precipitated or adsorbed, and these three processes control the dissolved copper concentrations and copper mobility and bioavailability. These processes have been reviewed by Flemming and Trevors (1989).

Inorganic Cu^{+2} complexes in water include complexes with OH and CO_3^{-2}, such as $Cu(OH)^+$ and $Cu(CO_3)_2^{-2}$. Due to this complexing with CO_3^{-2}, the bioavailability of copper decreases with increasing water hardness. In surface waters, Cu^{+2} will form complexes with a wide range of organic compounds, such as humic and fulvic acids. In fresh river water, 76 to 99% of copper can occur as organic complexes (Flemming and Trevors 1989).

Copper can precipitate in natural waters as a number of secondary minerals, including copper hydroxide ($Cu(OH)_2$) and malachite, reducing the bioavailability of copper. In sediments, copper can be adsorbed by clay minerals, oxides, and organic matter. Factors which influence the adsorption of copper include pH, and the concentrations of copper and possible adsorbents as well as competing cations. Adsorption peaks at a pH of about 7. Desorption of copper will occur, particularly in the presence of high concentrations of competing cations such as Ca^{+2} and Mg^{+2} (Flemming and Trevors 1989).

Mercury

Mercury (Hg) is a metal which can exist in one of three oxidation states, Hg(0), Hg(+I) and Hg(+II). Mercury is unique because elemental mercury exists as a liquid at room temperature (NRCC 1978). Elemental mercury is rare in nature, but it commonly occurs in solid solution with native gold and silver (Berry *et al.* 1983). The most common primary mercury mineral is cinnabar, HgS, which is an important mercury ore mineral but is rare in Canada (Eckstrand 1984). Mercury can also occur in a number of sulphide minerals, particularly tetrahedrite ($Cu_{12}Sb_4S_{13}$), an ore of copper which can contain up to 1000 μg/g mercury (NRCC 1978). Few secondary mercury minerals exist.

Once released to the environment, the biogeochemical cycling of mercury is complex, with bacterially mediated transformations playing an important role in the cycling. In natural, aerobic waters elemental mercury is normally oxidized so that the dominant inorganic species are Hg(+II) species, typically complex ions (CCREM 1987). An important process in the removal of inorganic mercury from the water column is the sorption of Hg(+II) onto suspended solids and bottom sediments. This process is dependant on the organic content of the sediment, and pH has little affect. Desorption rates from sediment are low (CCREM 1987).

Microorganisms in sediment, the water column and within organisms can methylate Hg(+II) under both aerobic and anaerobic conditions, although rates tend to be higher in aerobic systems (CCREM 1987). The rate of methylation is pH dependant. The methylation rate in lake water at a pH of about 4.5 has been reported to be about seven times faster than the methylation rate at a pH of about 8.5 (D'Itri 1991). Dimethylmercury ($(CH_3)_2Hg$) tends to be formed at high pH and low Hg(+II) concentrations, while lower pH and higher concentrations favour the formation of methylmercury (CH_3Hg^+)(CCREM 1987). Once formed, some methylmercury is lost to the atmosphere through volatilization, but almost all methylmercury is absorbed by organisms (D'Itri 1991).

Bacteria in sediments and possibly the water column are capable of demethylating methylmercury, producing elemental mercury and methane. This process helps to reduce methylmercury concentrations, but the rate of demethylation tends to be lower than the rate of methylation, so an excess of methylmercury is almost always available for absorption by organisms (D'Itri 1991).

Atmospheric cycling is very important in the biogeochemical cycle of mercury, since elemental mercury, and some other forms of mercury, are volatile. The predominant mercury species in the atmosphere is elemental mercury, but methylmercury has been reported. Mercury also occurs in airborne particulate matter, although the particulate fraction is normally less than 4 % of the total mercury in the atmosphere (D'Itri 1991). Volatilization of mercury from waterbodies can be a mechanism for the removal of mercury, but mercury is removed from the atmosphere by means of particulate fallout and dissolution in precipitation, resulting in the recontamination of surface water (D'Itri 1991). Atmospheric transport of mercury from contaminant sources can be an important source of surface water contamination (NRCC 1978).

Nickel

Nickel (Ni) has six possible oxidation states, from Ni(-I) to Ni(+IV), but the most common oxidation states in nature are Ni(0) and Ni(II) (Stoeppler 1980). The Ni(III) and Ni(IV) states are relatively stable, but are comparatively rare (NRCC 1981).

Primary nickel minerals include sulphide minerals such as pentlandite ($(Fe,Ni)_9S_8$), which is the most important ore of nickel, arsenide and sulpharsenide minerals such as nickeline (NiAs) and gersdorffite (NiAsS), and in a number of silicate minerals such as serpentine ($(Mg,Fe,Ni)_3Si_2O_5(OH)_4$) (Berry *et al.* 1983). Chemically, nickel is very similar to both iron and cobalt, so it can replace iron and cobalt in primary minerals such as pyrite (FeS_2), pyrrhotite ($Fe_{1-X}S$) and cobaltite (CoAsS), and a wide range of silicate minerals in which iron occurs (Berry *et al.* 1983). Secondary minerals in which nickel can occur include sulphates, arsenates, carbonates, oxides, and clay minerals. Oxidation and dissolution of secondary nickel minerals result in the release of nickel to the environment.

In aquatic systems, nickel can occur as dissolved species, or as soluble salts adsorbed onto or associated with clay minerals, iron and manganese oxides, or organic matter. Factors affecting the form in which nickel occurs in aquatic systems, as well as its fate in such systems include pH, Eh, ionic strength, type and concentration of organic and inorganic ligands, and the presence of solid surfaces for adsorption (Nriagu 1980). In natural waters, at a pH of 5 to 9, Ni^{+2} is the dominant nickel species, and where sulphate concentrations are high, highly soluble $NiSO_4$ may be the dominant nickel species (Nriagu 1980). Below a pH of 6 nickel is highly mobile, and sorption plays a minor role in nickel transport and availability (CCREM 1987).

1.7.4 Influence of Glaciation

The presence of glacial material derived from mineral deposits may impact mining and environmental control and remediation in four main ways:

1) Ore minerals found in glacial materials can be traced back to the distant exposed or hidden mineralized outcrops from which the glacier eroded and transported them, aiding in the

mineral exploration process;

2) Glacial till in the vicinity of mineral deposits may be enriched in ore minerals and associated minerals. If the deposit is mined, the mineralogy and chemistry of the tailings and waste rock would be similar to that of glacial deposits. Examination of the long term stability of the glacial till may give an indication of the expected long term stability of the mine wastes;

3) Oxidation and leaching of ore minerals in the glacial till may be resulting in surface water contamination in the vicinity of a mineral deposit. This source of natural contamination should be considered when planning environmental control, monitoring programs and remediation measures at the site, if the deposit is mined;

4) Glacial materials are often used at mine sites as backfill, building material for roads, and in environmental control and remediation measures such as covers, dams and dikes for tailings or waste rock, and as buffering diluents in treatment systems. Since the glacial material may be naturally contaminated, the source and composition of glacial material to be used should be considered to ensure that surface water contamination does not occur as a result of the use of naturally contaminated glacial material.

2 Metal Mining and Milling Processes in Canada

This section describes the main phases in the life of a mine: Advanced Exploration and Mine Development; Mine Operation; Ore processing; and Mine Closure. Advanced exploration occurs at some mineral deposits identified during preliminary exploration (not covered in this section). Only a small number of mineral deposits identified during preliminary exploration show sufficient promise to proceed to the much more costly stage of advanced exploration. If feasibility studies conducted during advanced exploration show that the deposit can be profitably mined, and funding is available, then mine development will begin. During mine development the ore body is accessed and prepared for mining, ore milling facilities are constructed, and site infrastructure is established. Once development is complete mining and ore processing is commenced. A mine can remain operating for a few years to many decades, depending on the size of the deposit and economic conditions. Once a mine can no longer extract minerals at a profit the mine is closed.

2.1 Advanced Exploration and Mine Development

Advanced Exploration

In areas where the results of preliminary exploration are positive, advanced exploration may commence, or there may be sufficient information about the deposit to proceed directly to mine development. At most modern exploration sites advanced exploration is required. The primary goals of advanced exploration are to define the quantity and quality of ore and to determine the most appropriate mining and processing methods.

Advanced exploration is frequently required before a commercial production decision is made, in order to reduce technical and financial uncertainties and attendant investment risks. A production decision is based on a feasibility study, which includes a preliminary engineering assessment of the technical and economic viability of mine development. The study estimates expected cash inflows from the sale of mineral products and expected cash outflows for mine development, operation and reclamation. The feasibility study also evaluates the sensitivity of project economics to key study parameters, including ore tonnage and grade, extraction and milling rates, metal prices, exchange rates, capital and operating costs, financial costs, and schedules.

As an example, surface diamond drill results may indicate the presence of a mineral deposit at depth. The tonnage and grade of the deposit can be estimated by geostatistical methods and the ore response can be evaluated by batch testing at a laboratory scale using core samples collected during the drilling. The resulting data may be used for preliminary mine layout, process design, and costing, but the level of uncertainty may be excessive for feasibility purposes, indicating an unacceptably high level of investment risk. There may be considerable uncertainty concerning the size and grade of the deposit. Confidence concerning the size and grade of the deposit could be increased by additional diamond drilling from surface, but excessive diamond drilling costs and inaccuracy due to drill deviation favour drilling from underground. Core samples used for batch testing may not be representative of the ore types that will be encountered during mining and conclusions concerning amenability to processing may be biased as a result. Larger ore samples are required to determine the optimal milling processing through continuous testing of major ore types at the pilot scale, particularly for ores that are complex and fine-grained.

Establishment of an exploration shaft or other underground mine workings allows the development of test stopes to evaluate mining methods and the extraction of representative ore samples for pilot testing, satisfying the second as well as the first goal of advanced exploration. Valuable data can also be acquired concerning rock quality, mineralogy and geochemistry and the quantity and quality of groundwater to be collected. Some infrastructure and environmental control facilities may also be developed at this stage.

There can be no assurance that commercial development will follow advanced exploration and the entire investment is therefore at risk, but the technical and financial risks associated with mine development will be considerably reduced as a consequence. A further benefit is that both the cost and the time required to reach production following a positive development decision may be reduced.

Mine Development

Mine development proceeds at a site where exploration has identified an ore deposit and the technical and economic viability of the project has been confirmed by a feasibility study.

The most significant activity during mine development is the establishment of underground or surface mine workings to provide direct access to the ore body. Water must be pumped from the workings due to groundwater flow into the workings. Water must also be provided for drilling, dust suppression and other uses, and removed from the workings. Mine water is pumped from the workings to surface for removal of suspended solids, and reuse or additional treatment prior to recycling or discharge. Surface mine development requires stripping of overburden and waste rock overlying the ore zone. Underground mine development is usually conducted in waste rock that does not contain economic metal values but may contain subeconomic levels of mineralization. Waste rock is typically stockpiled on surface. No ore processing is conducted, but ore may be stockpiled as mine workings are established.

The last step of the mine development phase is to construct ore processing and waste management facilities, and complete final preparations for production, including the construction of administrative facilities and accommodation.

2.2 Mine Operation

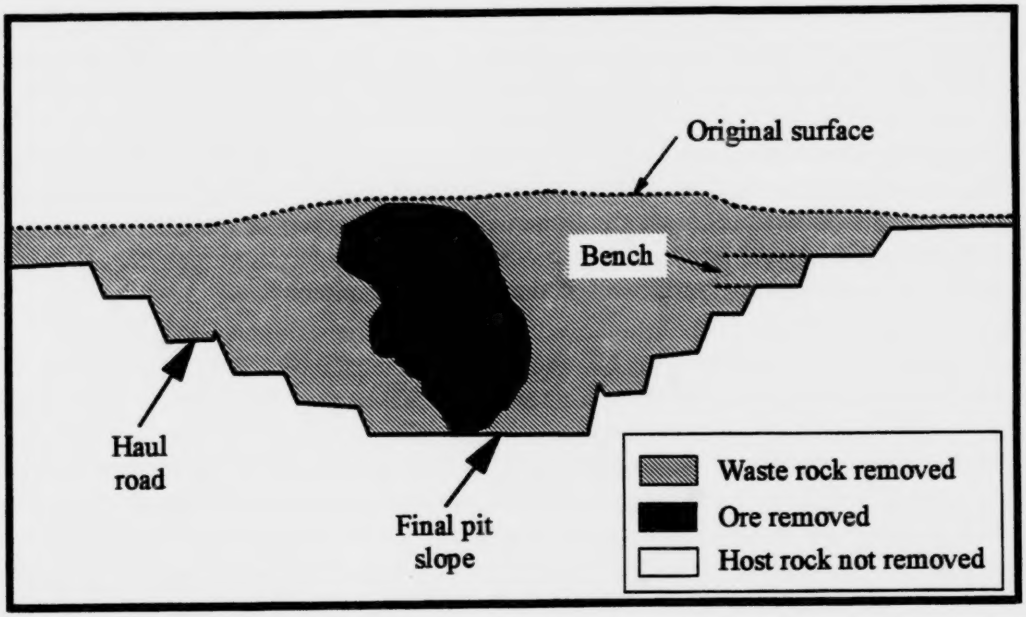
Ore can be extracted either from surface mines or underground mines. The general term "surface mine" may include open pit mines or strip mines as well as pits and quarries from which sand, gravel and rock are commonly extracted. Strip mining is applicable only to planar, near surface deposits covered by overburden, and is used chiefly for the extraction of coal. In a metal mining context, the term "surface mine" denotes an open pit mine.

Surface Mines

Surface mines are preferred for the extraction ore close to the surface. Under these conditions, an open pit mine may extract a greater portion of the ore at a lower operating cost than an underground mine. In some cases, ground conditions may preclude extraction by underground methods or cause underground workings to break through to the surface. In 1990, 30% of mines in Canada were surface mines, but those surface mines extracted 71% of all ore in Canada (*Canadian Mining Journal* 1991). Open pit mining has been conducted in all regions and is the predominant method for extraction of copper ores in British Columbia and iron ores in Quebec and Labrador. Open pit mining has also found occasional application to the extraction of copper-lead-zinc and gold ores.

Open pit sizes vary widely, with the largest active open pit in Canada, in Logan Lake, BC, being 6700 x 2000 x 360 metres (*Canadian Mining Journal* 1991). Open pits are generally much wider than they are deep in order to ensure the stability of the pit walls (see Figure 2). The stripping ratio, the ratio of waste rock to ore, varies dramatically over the life of an open pit mine and depends on the geometry of the ore body, ore grades, and metal price variations. Open pit mines generally produce larger volumes of waste rock than ore. The waste rock is most commonly disposed of on surface, but alternative approaches have been proposed or implemented for a number of recent developments.

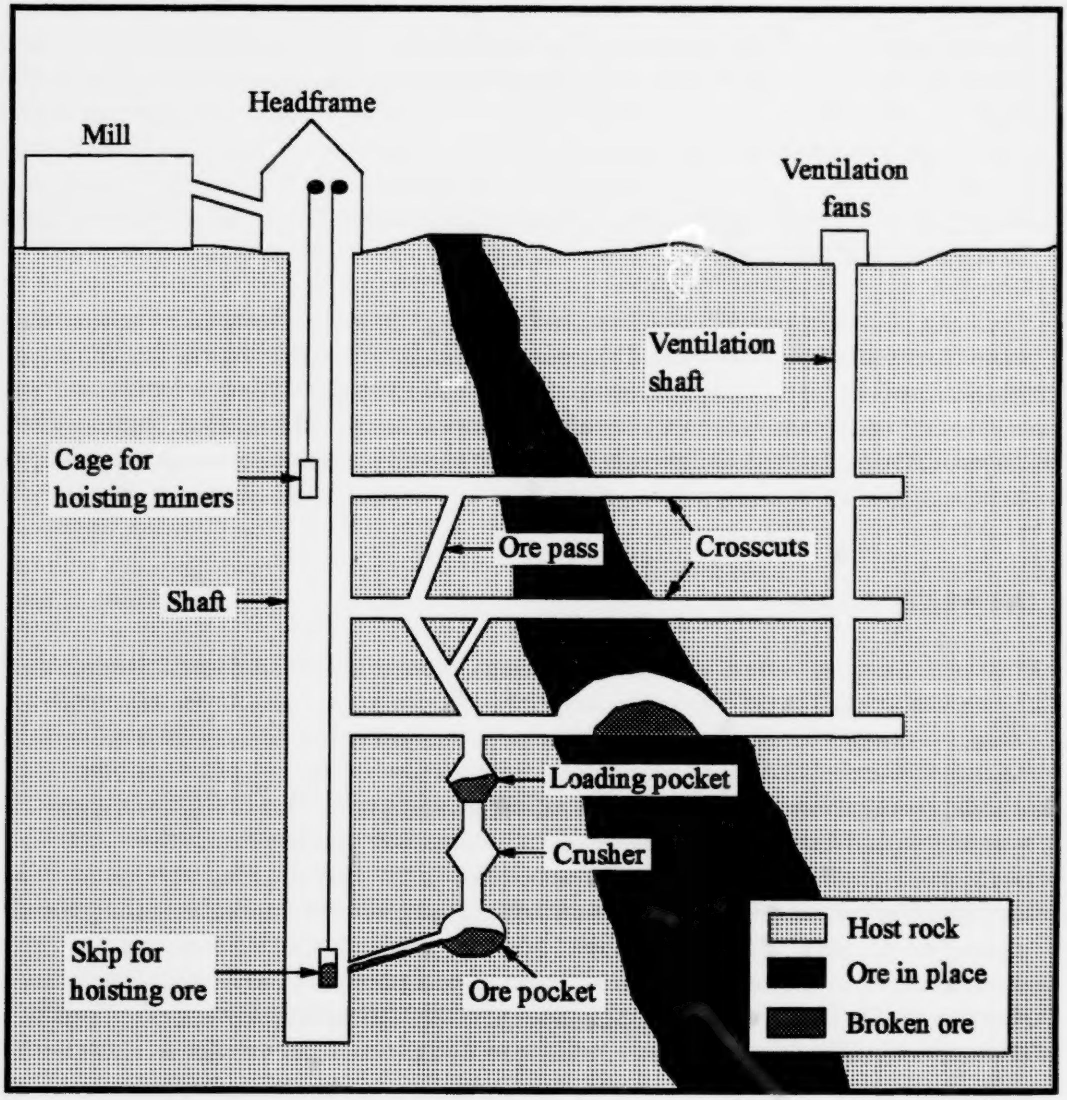
Figure 2: Cross section through a typical open pit mine (after Marshall 1982)



Underground Mines

Deeper or more irregularly shaped ore bodies are mined by underground methods, resulting in less surface disturbance (see Figure 3). Extraction is more selective than in open pit mining and waste rock is generated primarily are a result of ongoing mine development. The quantity of ore extracted generally exceeds the quantity of waste rock generated, often by a wide margin. Segregation of ore and waste rock is typically inconvenient and sometimes difficult. As a result, the rock sent to the mill for further processing, called the mill feed, may contain some waste rock in addition to ore. This results in some dilution of the mill feed, but maximizes recovery of the ore. In about one half of Canadian underground mines waste rock that is segregated from the ore is used as mine backfill to provide roof and wall support underground. Waste rock that is not required as backfill is disposed of on surface.

Figure 3: Cross section through a typical underground mine (after Marshall 1982)


Headframe
Mill
Ventilation fans
Ventilation shaft
Cage for hoisting miners
Ore pass
Crosscuts
Shaft
Loading pocket
Crusher
Skip for hoisting ore
Ore pocket
Host rock
Ore in place
Broken ore

Mine Dewatering

Mine dewatering is a continuous activity at both underground and surface mines. It is made necessary because of groundwater flow into the mine workings, and the use of water in mine operations such as dust control. Water is pumped from the mine to a surface settling pond that removes particulates by gravity sedimentation. Water may also be treated to remove dissolved substances prior to final discharge or reuse.

Reworking of Mine Wastes

Technological advances and economic factors may create opportunities for reprocessing of mine wastes. Reprocessing is most commonly applicable for old gold and silver mine wastes with relatively high grades and gross metal values that may approach or exceed those for ores in contemporary mines. Reworking of mine wastes has been conducted in areas such as Timmins, Kirkland Lake and Cobalt in Ontario. While reprocessing is most commonly applied to tailings and similar wastes, waste rock is also reprocessed at some sites.

2.3 Ore Processing

Once ore is extracted from a mine it must be processed to recover the valuable minerals. Ore typically consists of small amounts of valuable minerals in close association with much larger amounts of waste minerals of no economic value (gangue). At mills the valuable minerals are separated (liberated) from the gangue to permit further processing by a smelter or refinery. Mills are most often located at the mine site to minimize transportation costs. Exceptions to this general rule include: cases where economic, environmental or other factors favour shipping of ore to an existing mill; cases where a mill may instead be located at a nearby smelter or refinery site; and rare cases in which a particular ore with a high gross metal value and other favourable characteristics may be shipped for direct processing by a smelter. Processing entails several operations which can be considered in the broad categories of comminution, separation and dewatering. The steps involved in the processing of ore are illustrated in a series of process flow charts presented in Appendix 1.

2.3.1 Comminution

Comminution is required to physically liberate valuable minerals prior to separation by physical and chemical processes. Broken ore is typically reduced in size by both crushing and grinding.

2.3.2 Crushing

A number of factors including energy efficiency, water management, and workplace hygiene favour the use of crushing for coarse size reduction followed by grinding for fine size reduction. Initial breakage of ore is accomplished within the mine by blasting. Primary crushing and sizing may be performed within the mine to reduce the size of ore prior to transportation to the mill. Further crushing is usually performed at the mill to reduce the ore to a size at which grinding becomes the preferred process. The most common crusher designs are the jaw crusher and the gyratory cone crusher. In either case breakage is the result of impact, with ore being crushed between a stationary plate or crusher bowl and an oscillating plate or rotating eccentric.

No chemicals other than lubricants and sometimes dust suppression agents are used during crushing. Water consumption is minimal and is generally limited to dust control, plant cleanup, and transport of dust to the grinding circuit. The crushed rock may be sized using a vibrating screen or other device, with the oversize rock being returned to the crusher and the undersize rock proceeding to the next stage of crushing and grinding. In total, as many as four stages of crushing may be required with two or three stages being most typical.

2.3.3 Grinding

Grinding is used to achieve finer size reduction. Grinding is conducted wet since the subsequent separation processes generally treat the ore as a slurry of fine mineral particles in water. Autogenous or semi-autogenous grinding is preferred if the ore characteristics are favourable. In autogenous grinding hard, abrasion resistant mineral components within the ore serve as the grinding media, while in semi-autogenous (SAG) grinding a synthetic grinding media is added to the ore to enhance the grinding. The most common types of synthetic grinding media are rods and balls. SAG rod mills are preferred for coarse grinding, while SAG ball mills are preferred for fine grinding, since the balls in the grinding media charge have a higher specific surface than rods, resulting in finer grinding.

One or more stages of grinding may be used, often operating in a closed circuit with a type of size classifier to achieve the desired grinding product size distribution. Classification of ore during grinding is commonly achieved using hydrocyclones. Influences on separation within hydrocyclones include particle size, shape and density, and slurry density. Coarse, heavy particles report to the classifier underflow and are returned to the grinding circuit for further size reduction. Fine, light particles report to the overflow, together with most of the water, and may be directed to another classification stage or to the separation circuit. Ore must be ground sufficiently to achieve adequate liberation of the valuable minerals and provide high concentrate grade and metal recoveries, but over grinding may lead to poor selectivity and excessive recovery losses in the subsequent separation processes. For fine grained ore, or complex ore types, a number of stages of regrinding and classification of intermediate products from the subsequent separation processes may be required to achieve the optimal balance between concentrate grade and metal recovery.

Wear parts within grinding mills such as mill lifters and liners are typically made of alloy steel or rubber. Chemicals such as lime, soda ash and sulphur dioxide may be added in the grinding circuit to modify the chemical behaviour or surface properties of various minerals, in preparation for subsequent separation processes. In some cases a viscosity modifier may be used to achieve finer grinding or increased throughput by allowing a higher density slurry to be processed by the grinding circuit.

Much of the water used in milling is added in the grinding circuit to achieve the desired slurry density. Water added in the grinding circuit is commonly recycled from the last stage of milling (dewatering after separation) to reduce consumption of fresh water, reagents and energy, as well as water treatment requirements, and environmental effects.

2.3.4 Separation

Most of the separation processes used in milling exploit differences in physical properties or behaviour of mineral particles. Examples include properties such as size, specific gravity (or density) and surface energy. The bulk of the mineral is not chemically altered, although some chemicals may be used to alter surface chemistry and energy of particular mineral particles to effect a cleaner separation. Chemical processes involving the preferential dissolution and precipitation of one or more minerals are also used, most notably for recovery of copper, uranium, gold and silver.

The mineral concentrates produced during ore separation are sent to smelters or refineries, at which further processing is conducted, resulting in production of pure metal for sale to manufacturers and other users. Smelting and refining processes are beyond the scope of this document.

2.3.4.1 Physical Separation Processes

Gravity Separation

Minerals can be separated on the basis of differences in specific gravity (or density). A prerequisite for gravity separation is to obtain a particle size that is amenable to gravity separation, while achieving adequate liberation of the valuable minerals. Gravity separation is generally ineffective for complex and fine grained polymetallic ores containing several minerals of similar specific gravity, unless the mill feed contains a significant amount of non-sulphide gangue. In this case, gravity separation may be used to preconcentrate the metallic minerals prior to further processing, thus increasing the grade of the mill feed, decreasing energy consumption, and permitting higher production rates.

Gravity separation is most widely used in Canada in the separation of iron ores and the recovery of native gold. Gravity separation has also been used for recovery of dense minerals including those containing tin, tungsten, tantalum and niobium.

Magnetic Separation

Minerals can be separated on the basis of differences in magnetic susceptibility. A prerequisite for magnetic separation is to achieve adequate liberation of the magnetic minerals during grinding. Advances in high intensity magnetic separator technology permit recovery of weakly or paramagnetic minerals using high magnetic field strengths and gradients and can achieve effective separation of minerals with relatively small differences in magnetic susceptibility.

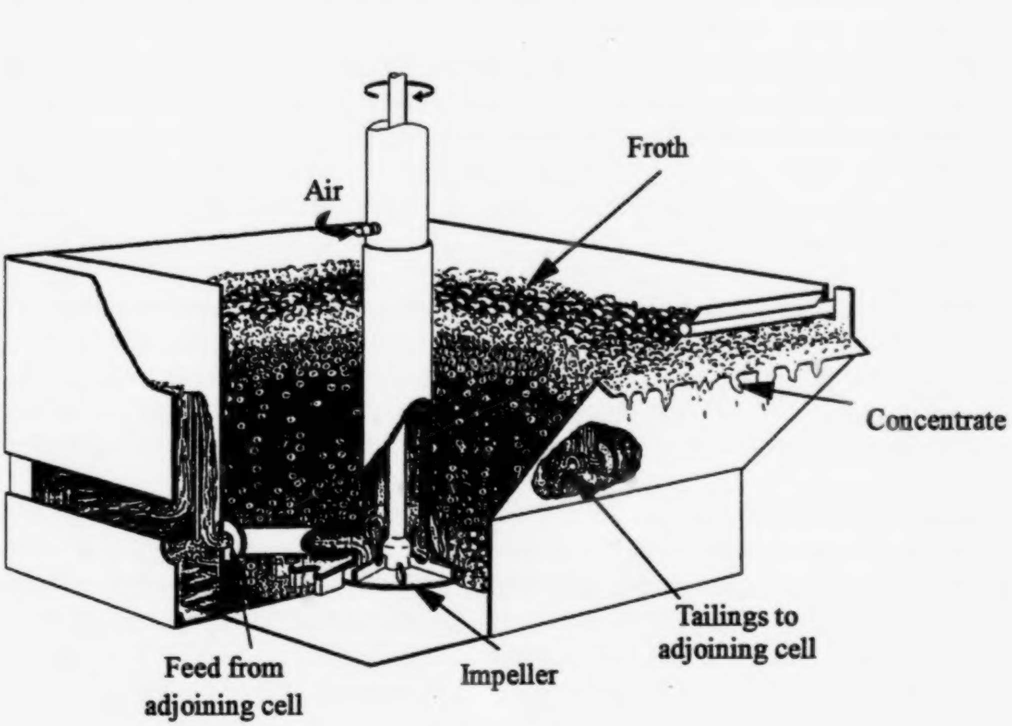
Magnetic separation has been used in Canada to separate iron ore from waste minerals, for removal of magnetite and pyrrhotite from base metal ores prior to flotation, and for recovery of magnetite from copper concentrates. Potential applications for improved separation of fine grained, complex sulphide concentrates are now being investigated based on recent experience elsewhere.

Flotation Separation

Flotation is used for the separation of a wide variety of minerals on the basis of differences in surface energy of various minerals in contact with air and water. It is the dominant process for the recovery of Canadian sulphide ores including those of copper, nickel, lead and zinc. It is also used for recovery of gold associated with sulphide minerals.

Flotation is based on the principle that some minerals exhibit lower surface energy in contact with air rather than water, while other minerals exhibit lower surface energy in contact with water. To separate minerals using this principle fine air bubbles are introduced into an agitated slurry of mineral particles in water. In this slurry mineral particles collide with air bubbles and hydrophobic minerals that favour contact with air preferentially attach to air bubbles and are subsequently levitated to the surface of the flotation cell. As air bubbles accumulate at the surface a stable froth forms and eventually overflows as the flotation cell concentrate. Hydrophilic minerals that favour contact with water remain in the slurry and report to the flotation cell tailings (Figure 4).

Figure 4: Cutaway view of a flotation cell (after Boldt and Queneau 1966)



Flotation is a kinetic process and the flotation rate depends in part on particle composition and size. Flotation concentrate grade and recovery also depend on the residence time distribution. A prerequisite for flotation is to achieve adequate liberation at a particle size that is amenable to separation by flotation. Particles that are too coarse are not amenable to flotation as they may be insufficiently liberated and their higher mass may cause them to be detached from a rising air bubble and drop back into the slurry. Particles that are too fine are not amenable to flotation as they may have insufficient momentum to collide with and attach to an air bubble or may drop back into the slurry as the froth drains prior to overflowing the cell. Grinding, classification and conditioning of the flotation feed must be carefully controlled and regrinding and classification of intermediate flotation concentrates or tailings may be required.

Minerals with similar flotation rates may be separated from other minerals and recovered together in a bulk concentrate for subsequent separation by flotation or processing by a smelter or refinery. Alternatively, minerals may be sequentially recovered by selective flotation or a combination of bulk and selective flotation. In either case, kinetic considerations preclude achievement of satisfactory concentrate grades and recoveries in a single flotation stage. Several stages are generally required for each concentrate to be produced. Flotation cells are generally configured in banks of several cells due to mixing and residence time considerations, with each stage consisting of one or more banks of flotation cells and with the tailings from one cell constituting the feed to the next. Regrinding and classification or conditioning of the feed with heat, air or chemical reagents may be required prior to a flotation stage in order to liberate individual mineral grains and alter the physical behaviour of mineral particles by chemical alteration of the mineral surface.

The principal flotation reagents used for the commercial recovery of copper, nickel, lead, zinc and associated metals in Canada are categorized as follows:

Frothers: used to promote the formation and stability of fine air bubbles and the development of a stable mineralized froth. Frothers may be either highly soluble or relatively insoluble in water. Most collectors also exhibit some frother characteristics.

One of the frothers most widely used in the mining industry for control of froth characteristics and process selectivity is MIBC (methyl isobutyl carbinol), which is a water soluble secondary alcohol. Dowfroth 250 (polypropylene glycol methyl ether) is used where stronger frothing conditions are required (E.A.G. 1992).

A number of flotation promoters are formulated by varying the excess of a reactant such as cresylic acid to allow mill operators to optimize process selectivity by selecting a product from a family of related products that provides the best balance between collector and frother characteristics for a particular application.

Collectors: while some minerals such as coal are naturally hydrophobic, a collector is generally required the enhance hydrophobic behaviour, in order to achieve a high flotation rate and recovery. Collectors render some minerals hydrophobic by forming insoluble metal salts on the surface of the mineral particles, while other minerals remain hydrophilic because the metal salts formed are somewhat more soluble. The selectivity of a collector therefore depends on the relative solubilities of the metal salts of interest. Most of the collector added to the flotation pulp is removed from solution by absorption or adsorption on mineral surfaces.

The most widely used collectors are xanthates (dithiocarbonates), notably, potassium amyl xanthate, sodium amyl xanthate and sodium isopropyl xanthate. Xanthates are readily soluble in water but form insoluble copper, lead and nickel salts and can therefore be used to recover copper, lead, nickel and activated zinc minerals. A number of other reagents may be used to increase selectivity against iron sulphides, increase recovery of precious metals or tarnished minerals or improve stability at low pH. The most common families include the dithio-phosphates and thionocarbamates, where the term dithiophosphates includes dithiophosphoric acids as well as sodium and ammonium salts.

pH regulators: reagents used to adjust pH for grinding and flotation. Alkaline conditions are preferred for recovery of base metals. Lime, in the form of quick lime (CaO), hydrated lime ($CaO{\cdot}H_2O$), or slaked lime $Ca(OH)_2$ is used to raise the pH. Soda ash (Na_2CO_3) may be favoured if lime depresses copper or other valuable minerals, or interferes with the flotation collector or promoter. Sodium hydroxide is occasionally used as a gangue slime regulator and sulphuric acid may assist in recovery of iron sulphides, particularly after depression by lime or cyanide.

Activators: metal ions including copper and silver may activate minerals that would otherwise be hydrophobic. Galvanic replacement reactions on the mineral surface result in the formation of a molecular layer of the more noble metal sulphide which in turn reacts with xanthate or other collectors or promoters, causing the mineral to respond to flotation like the more noble copper or silver sulphide mineral. The most common example of the use of an activator is the addition of copper sulphate to a flotation pulp containing the zinc sulphide mineral sphalerite, ZnS. The cupric ion attaches to the sphalerite, allowing the mineral to be floated with a xanthate.

Depressants: aeration may be used to depress pyrite and sulphur dioxide or zinc sulphate may be used to depress zinc in the flotation of complex sulphide ores. Heat may be used to depress lead and zinc minerals. Starch or other organic colloids may be used to depress lead for recovery of copper from a bulk copper-lead concentrate and soluble metal dichromate and permanganate salts have been used in similar applications to depress lead and zinc by oxidizing both residual reagents and the surface of the mineral itself. Cyanide may also be used at very low concentrations to depress pyrite but tends also to depress copper and lead.

Modifiers: a wide variety of other reagents may be used in specific applications. One example is the use of activated carbon for desorption of collectors and promoters from mineral surfaces. Another example is sulphidizing, using sodium sulphide to aid in the flotation of oxidized copper and lead ores. The reason for the effectiveness of sulphidizing is not certain, though it is probably related to the formation of a new mineral surface simulating that of the unoxidized sulphide mineral. After sulphidizing, the oxidized mineral is floated with a xanthate or similar collector.

2.3.4.2 Chemical Separation Processes

Chemical processes alter the bulk of the mineral feed and are widely used for the metallurgical processing of mineral concentrates. Hydrometallurgical processing or leaching involves the preferential dissolution and precipitation of one or more minerals and is also used for direct processing of ores at the mine level, most notably for recovery of copper, uranium, gold and silver. Typical applications in each case are briefly described below:

Copper

Most Canadian copper ores contain sulphide minerals that can be recovered by flotation, but ore zones with oxidized copper minerals may not be amenable to flotation. Oxidized ores can be directly leached with sulphuric acid at atmospheric pressure and temperature. The resulting copper-bearing (pregnant) solution can be treated by solvent extraction (SX) or ion exchange (IX) for removal of iron prior to recovery of copper by electrowinning, with the spent electrolyte being returned to the leach circuit. The IX and SX processes consist of two main steps, adsorption and desorption (elution). Adsorption is the removal of a metal (iron) from the pregnant solution by loading (adsorption) on the IX resin or on an SX organic solvent. Desorption is the removal of the metal (iron) from the resin or solvent with sulphuric acid. In other cases it may be feasible to recover copper from the pregnant solution by cementation on shredded scrap metal for further processing at a copper smelter.

Uranium

In Canada, uranium mines are located in Ontario (Stanleigh Mine) and Saskatchewan (Cluff Lake, Key Lake, Rabbit Lake Mines). At these sites uranium is extracted from the ores by the acid leach method.

The ore is prepared for acid leach by crushing, grinding and thickening to expose the uranium bearing minerals. The thickened slurry is leached using sulphuric acid. A pregnant leach solution containing the dissolved uranium is separated from the leached ore by decantation with the aid of flocculants. The pregnant solution is impure and therefore requires upgrading before uranium may be precipitated. Typically, the pregnant solution is purified by ion exchange (IX) or solvent extraction (SX). In this process the uranium is selectively removed from the pregnant solution by adsorption on the IX resin or on an SX organic solvent. The uranium is then removed from the resin or solvent by desorption by an elution solution containing an acid (nitric or sulphuric) or a base (Na_2CO_3). At the Stanleigh Mine IX is used for solution purification whereas SX is used at all operations in Saskatchewan.

Uranium is precipitated from the purified solution as "yellow cake" by the addition of gaseous ammonia, magnesia (MgO) or hydrogen peroxide. In the case of ammonia addition (Key Lake) uranium is precipitated as ammonium diuranate ($(NH_4)_2U_2O_7$). At the Stanleigh and Cluff Lake operations, magnesia is used to precipitate magnesium diuranate (MgU_2O_7) while at Rabbit Lake, hydrogen peroxide is used to precipitate U_3O_8. The yellow cake is dewatered and dried before shipping to a uranium refinery.

Gold and Silver

The preferred process for recovery of gold and silver depends on the mineralogy of the ore. Free gold and silver and liberated gold and silver minerals may be recoverable either by gravity separation or flotation. For most ores, all or most of the precious metal values are associated with other minerals and chemical processing is required.

The dominant method for recovery of metallic gold or silver that is exposed but unliberated is dissolution by cyanidation. A dilute solution of calcium or sodium cyanide is used to extract precious metal values as cyanide complexes. Gold is first dissolved from its ore by a dilute alkaline cyanide solution according to the following reaction:

Equation 10 $$4\,Au + 8\,NaCN + O_2 + 2\,H_2O \rightarrow 4\,NaAu(CN)_2 + 4\,NaOH$$

Following cyanidation the gold-bearing (pregnant) solution is separated from tailings solids, usually by vacuum filtration followed by clarification. After separation, metal values are commonly recovered from the pregnant solution by absorption directly from the leach slurry onto activated carbon granules in the Carbon-in-Pulp (CIP) process. The activated carbon is then stripped of the gold, reactivated and returned to the circuit to be reused. An alternative approach, the Merrill-Crowe process, may be used. In this process zinc dust is added to the pregnant solution, causing the precious metals to precipitate from the solution.

Following gold precipitation, most of the gold-free (barren) solution is recycled back to the cyanidation process to take advantage of its residual leaching ability for gold. However, part of the barren solution has to be discarded to prevent the build-up of contaminants that interfere with gold dissolution and/or precipitation. Contaminants such as metallo-cyanide complexes with ions of copper, iron, nickel or zinc form in the cyanide solution during gold leaching because cyanide is a powerful and non-selective solvent.

Several approaches other than cyanide leaching may be used for recovery of gold from a particular ore. High grade ores containing siliceous gangue minerals, possibly in combination with copper or lead mineralization, may be used as a flux for a copper or lead smelter. Refractory ores in which fine gold is associated with waste sulphide minerals such as pyrite or arsenopyrite as fine inclusions may be roasted to expose the gold prior to cyanidation. This technique is no longer in common use due to atmospheric emissions of sulphur dioxide and arsenic, and liquid effluent discharges. Gold recovery from refractory ores is now commonly accomplished by the use of pressure oxidation or biological leaching rather than roasting. Gold that is associated with valuable sulphide minerals may be recovered by bulk or selective flotation of sulphide minerals and processed by a roaster or by a copper or lead smelter.

2.3.4.3 Reagent Consumption During Ore Processing

Chemical reagents are relatively expensive and, as such, the mining industry endeavours to use them wisely and with little waste. Order of magnitude estimates of the total quantity of reagents used daily by the Canadian metal mining industry are based on information from those mines reported in the "Status Report on Water Pollution Control in the Canadian Metal Mining Industry (1990 and 1991)", and a draft (1994) of "A Review of the Status of Gold Mine Effluent Control and Compliance in Canada" (ADI Nolan Davis, 1994). Actual sources of information for the estimates include Southam Mining Group's Mining Sourcebook (1993, 1994), MISA data, and consultants' reports.

Mines are divided into four categories: base metal, iron ore, uranium and gold. The daily consumption rates for the variety of reagents for each category of mine are shown in Table 3. The pH modifier item excludes lime but includes sodium carbonate, sodium hydroxide, nitric acid, hydrochloric acid and sulphuric acid which is also used in large quantities for leaching uranium ores. Lime is estimated separately because it is inexpensive, and widely used in large quantities. The consumption estimates in the gold mine category are presented for gold mines with and without cyanidation.

As shown in Table 3, uranium mines are the largest reagent consumers. About 75% of the reagent consumption is sulphuric acid which is used mainly in the leaching unit operation of uranium processing. On the other hand, iron ore mines use the least reagent because concentration of iron ore minerals, hematite and magnetite, is based on gravity and magnetic separation. More detailed information on reagent consumption is given in Appendix 2.

In Tables 4, 5 and 6 the consumption rates of bulk chemicals, frothers and collectors, and modifying agents and flocculants, respectively, are presented on a sector by sector basis.

Table 3: Total estimated reagent consumption in metal mining and milling (tons/day)

Category	STPD Ore Milled	Frother	Collector	Lime	Cyanide	pH Modifier	Activator	Flocculant/ Coagulant
Base Metal	591,482	15.02	42.12	502.17	21.40	82.79	52.51	6.38
Iron Ore	286,990							7.17
Uranium	34,243	52.55	18.94	502.46		1,953.76		8.59
Gold, with cyanidation	82,709	2.45	6.93	150.21	87.82	7.96	12.97	1.13
Gold, no cyanidation	2,940	0.07	0.22					0.05
Total	998,365	70.09	68.21	1,154.84	109.22	2,044.51	65.48	23.32

Table 4: Bulk chemicals used in metal mining and milling

Bulk Chemicals	Consumption lb./ton ore milled	Reagent Usage by Ore Type			
		Base Metal	Gold	Uranium	Iron Ore
Sulphuric Acid	70 - 97	pH regulator	pressure oxidation, effluent treatment	leaching	
Nitric Acid	0.9 - 5.4		carbon elution	leaching	
Hydrochloric Acid	0.08 - 7.4		carbon elution		
Calcium Hydroxide and Calcium Oxide	variable	pH regulator, flocculant		pH regulator	
Sodium Carbonate (Soda ash)	variable	pH regulator, to improve grades			
Sodium Hydroxide (Caustic soda)	variable		pH regulator		

Table 5: Principal frothers and collectors used in metal mining and milling

Chemical	Consumption lb./ton ore milled	Reagent Usage by Ore Type			
		Base Metal	Gold	Uranium	Iron Ore
Frothers					
Dowfroth 250	0.02 - 0.186	frother	frother		
Dowfroth 319	0.02 - 0.1	frother			
MIBC (methyl isobutyl carbinol)	0.002 - 0.08	frother	frother		
Pine Oil	0.002	frother			
Aerofroth G65	0.003	frother			
Collectors					
Potassium Amyl Xanthate	0.001 - 0.074	collector	collector		
Sodium Isopropyl Xanthate	0.033 - 0.3	collector	collector		
Sodium Amyl Xanthate	0.1	collector			
Sodium Diethyl and Sodium Butyl Dithiophosphate	0.18	collector			

Table 6: Principal modifying agents and flocculants used in metal mining and milling

Chemical	Consumption lb./ton ore milled	Reagent Usage by Ore Type			
		Base Metal	Gold	Uranium	Iron Ore
Modifying Agent					
Slaked Lime	variable	pH regulator	pH regulator	pH regulator	
Sodium Carbonate	3.2 - 5.4	pH regulator			
Sodium Hydroxide	0.208	pH regulator	pH regulator		
Sulphuric Acid	variable	pH regulator			
Copper Sulphate	0.02 - 2.26	activator			
Sodium Sulphide	0.005	activator			
Lead Nitrate	0.04 - 0.624	activator	to assist in gold precipitation		
Sodium Cyanide	0.05 - 1.0	depressant	gold dissolution		
Flocculant					
Percol 155	0.1	flocculant	flocculant	flocculant	flocculant
Percol 338	0.01	flocculant	flocculant		
Percol 351	0.002 - 0.8	flocculant	flocculant	flocculant	
Percol E10	0.002 - 0.15		flocculant		
Percol E24	0.12			flocculant	
Superfloc N100	0.0075		flocculant		
Allied Colloids E10	0.001 - 0.065	flocculant			

2.3.5 Dewatering

The concentrates obtained from most of the separation processes described in Section 2.3.4 are slurries with high water content. Prior to further processing, these slurries must be dewatered to reduce their water content. Tailings may also be dewatered prior to disposal. Dewatering involves two processes; thickening and filtration.

Thickening

Slurries are thickened by gravity settling. The excess water is decanted off and may be recycled in the mill processes. Chemical reagents may be added to cause finer grain material to flocculate and settle out of suspension.

Filtration

After thickening, the slurry is passed through a vacuum filter which traps the particulates. Most of the remaining water is removed.

2.4 Environmental Management During Mining and Ore Processing

The processes involved in mining and ore processing are illustrated in Figure 5. During mining wastewater may be produced as a result of mine dewatering and drainage from waste rock. Significantly greater volumes of wastewater are generated during ore processing operations such as grinding and concentrating, which use up to 4 tonnes of water per tonne of ore milled. Wastewater from mine operations may be contaminated as a result of the mineralogy of the deposit, and as a result of the loss to effluents of chemicals for milling and other activities. Prior to discharge wastewater must be treated in order to meet regulated effluent quality limits and to protect the receiving environment.

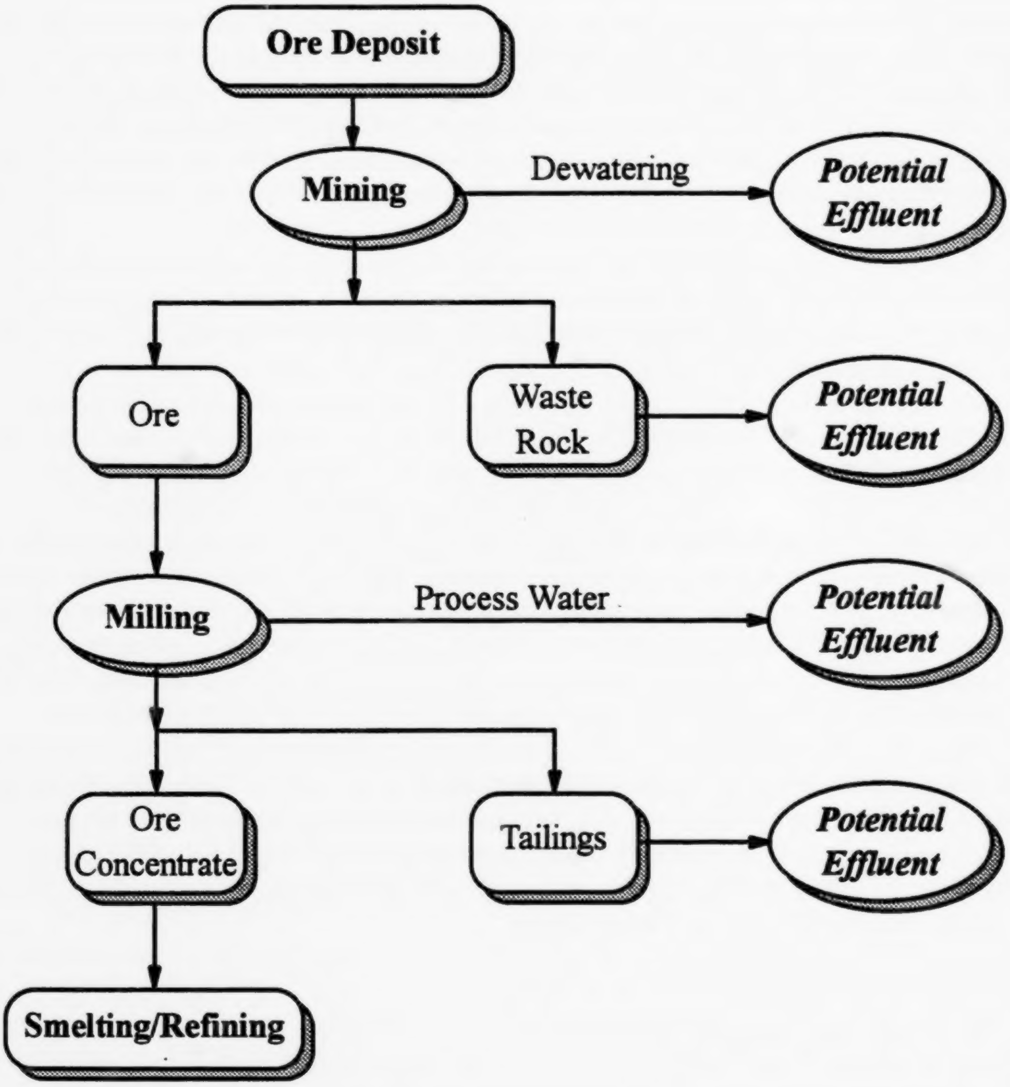
2.4.1 Contaminants Due to the Deposit Mineralogy

Acidic Drainage from Mine Wastes

The composition of water discharging from waste rock and tailings depends partially on the mineralogical composition of the rock. As discussed in Section 1.7.1 sulphide minerals in the presence of oxygen and water will oxidize, yielding sulphuric acid. As a result of this oxidation, the water discharging from waste rock and tailings may be strongly acidic. This problem is termed acid mine drainage (AMD) or acid rock drainage (ARD).

However, due to the presence of buffering minerals, such as calcite ($CaCO_3$), AMD will not always occur. The amount of buffering which occurs in the mine waste depends on the relative proportions of sulphides and carbonates. Whether or not waste will generate acid depends on whether the acid generating capacity is exhausted first, or the buffering capacity is exhausted first.

Figure 5: Processes involved in mining and ore processing


Ore Deposit
Mining
Dewatering
Potential Effluent
Ore
Waste Rock
Potential Effluent
Milling
Process Water
Potential Effluent
Ore Concentrate
Tailings
Potential Effluent
Smelting/Refining

Metals and Ions

Wastewater from mining and ore processing can contain metals naturally occurring in the ore and host rocks, particularly aluminium, arsenic, cadmium, copper, iron, lead, manganese, molybdenum, nickel and zinc. Wastewater from uranium deposits can contain radium-226. Metals are relatively soluble in water at low pH, so the concentrations of metals are frequently elevated in acid mine drainage environments. At higher pH most metals are relatively insoluble, so water with a neutral pH normally contains lower concentrations of metals. When low pH solutions are neutralized most metals will precipitate from solution as metal hydroxides. Exceptions to this are arsenic and molybdenum, various species of which are soluble in water over a wide pH range.

In addition to metals, ions associated with the ore or formed as a result of chemical alteration of the ore may occur in wastewater. The most common such ion is sulphate, formed as a result of the oxidation of sulphide minerals.

Suspended Solids

The recovery of economic minerals from ores produces wastewater containing suspended solids ranging from colloidal (non-settleable) to settleable materials. Similarly, mine waters and surface drainage in contact with ores, tailings, and waste rock usually contain suspended solids.

Thiosalts

Thiosalts originate mainly in the grinding and flotation of a number of sulphide ores, particularly those containing pyrite and pyrrhotite, under alkaline conditions. The three thiosalt species of major concern include thiosulphate ($S_2O_3^{2-}$), trithionate ($S_3O_6^{2-}$) and tetrathionate ($S_4O_6^{2-}$). Thiosalts are of concern because they can oxidize in water to the more stable form, H_2SO_4, thereby lowering the pH of the receiving water.

2.4.2 Loss of Chemicals to Effluent

In milling operations, most of the liquids used during the milling of ore are recycled. However, as the concentrations of various chemicals increase in these solutions, their effectiveness decreases, and they must be discarded. These spent solutions are commonly discarded into the tailings pond, and as a result wastewater from tailings from flotation mills may contain flotation agents, such as xanthates, or the byproducts of flotation agents. Wastewater from tailings from gold cyanide mills may contain cyanide, or cyanide byproducts.

Flotation Reagents

As described in Section 3.2.1.3 a wide range of flotation reagents, mostly organic chemicals, are used. The stability of these reagents in the environment varies, and some may breakdown to release chemicals which may be harmful in the environment. Some of these potentially harmful breakdown products are considered to be Priority Substances under the *Canadian Environmental Protection Act*.

The most widely used frothers in the mining industry are MIBC and Dowfroth 250. Dowfroth 250 contains the methyl ether component of two Priority Substances, bis(chloromethyl) ether (BCME) and chloromethyl methyl ether (CMME). These compounds are quite stable, and are not expected to breakdown to produce additional Priority Substances.

Most collectors used in the industry are xanthates, notably sodium and potassium xanthate and isopropyl xanthate. These compounds are comparatively stable in alkaline conditions, but may form alcohols and carbon disulphide under acidic conditions. Dithiophosphate collectors are not expected to give rise to the formation of Priority Substances. Two common collectors, Aerofloat 241 and 242, contain aromatic hydrocarbons, so they may breakdown to form Priority Substances (E.A.G. 1992).

Information on concentrations of flotation reagents and their breakdown products in wastewater are limited. Concentrations of xanthate in the range of 0.2 to 1.2 mg/L and dithiophosphate in the range of 0.3 t 2.7 mg/L have been reported (OMOE 1977). In 1987 ZENON Environmental Inc. undertook a project on behalf of the Ontario Mining Association to characterize effluent stream types from ten mining and milling operations in Ontario as requested by the Ministry of the Environment of Ontario under the MISA pre-regulation monitoring program. Flotation reagents or reagent breakdown products were detected were at one plant. The substance detected was a breakdown product of pine oil, which was subsequently replaced by methyl amyl alcohol (OMOE 1989).

Cyanide Compounds

During gold recovery using cyanide most of the gold-free (barren) cyanide solution is recycled back to the cyanidation process after gold precipitation to take advantage of its residual leaching ability for gold. However, cyanide also dissolves metals such as copper, iron, nickel and zinc, and once in solution these ions can react with cyanide to form metallo-cyanide complexes such as ferrocyanide. These metallocyanide complexes contaminate the cyanide solution, reducing the efficiency of gold dissolution and precipitation. To prevent this contamination, part of the barren solution has to be discarded to tailings. As a result wastewater from tailings from cyanide mills may contain a range of cyanide compounds.

Cyanide is also used in very small amounts at some base metal processing plants as a depressant for selected metallic sulphides. Thus, cyanide compounds may also occur in wastewater from tailings from some base metal flotation mills.

The aqueous chemistry of cyanide is complex, and cyanide compounds which can be present in wastewater include:

- cyanide ion (CN^-)
- hydrogen cyanide (HCN)
- cyanate (CNO)
- thiocyanate (CNS)
- alkaline earth salts (*e.g.* NaCN, KCN)
- metallocyanide complexes with metals such as:
    - gold ($Au(CN)_2^-$)
    - zinc ($Zn(CN)_2$, $Zn(CN)_4^{2-}$)
    - cadmium ($Cd(CN)_2$, $Cd(CN)_3^-$)
    - copper (CuCN , $Cu(CN)_3^{2-}$)
    - nickel ($Ni(CN)_2$, $Ni(CN)_4^{2-}$)
    - iron ($Fe(CN)_6^{4-}$)

These compounds vary considerably in their stability and in their solubility in water. The soluble, or weak acid dissociable (WAD) cyanide compounds include cyanide ion, hydrogen cyanide, and complexes of cadmium, copper, nickel, silver, and zinc. Less soluble to insoluble cyanide compounds include iron cyanides.

Cyanide concentrations in solution can measured as either weak acid dissociable cyanide, or as total cyanide, which includes complex iron cyanides, weak acid dissociable cyanide and most other inorganic cyanide complexes except those with gold, cobalt and some of the platinum metals.

The concentrations of total cyanide measured in the metal mining sector effluents are:

- gold mining effluent (with cyanidation) 0.005 - 0.374 mg/L (ADI Nolan Davis 1994)
- base metal effluent 0.001 - 0.074 mg/L (MOE 1992)

The concentrations of weak acid dissociable cyanide measured in the metal mining sector effluents are:

- gold mining effluent (with cyanidation) 0 - 0.293 mg/L (ADI Nolan Davis 1994)
- base metal effluent 0.0005 - 0.014 mg/L (MOE 1992)

2.4.3 Wastewater Treatment Technologies

To meet regulated effluent discharge limits and protect effluent receiving environments wastewater from mining and ore processing commonly requires some form of treatment before discharge. At present wastewater treatment is practised in Canada mainly through pH adjustment to remove dissolved metals (mainly arsenic, copper, iron, lead, nickel and zinc) by chemical precipitation and by physical settling to remove suspended solids. Other potential contaminants in mine/mill effluents which must be managed are:

- cyanide: by natural degradation, oxidative chemical processes
- thiosalts: by oxidative chemical processes
- radium-226: by precipitation with $BaCl_2$ addition

As part of the Ontario Ministry of the Environment's (OMOE) Municipal/Industrial Strategy for Abatement (MISA) program examining the metal mining sector Kilborn Inc. and The Environment Applications Group Limited were retained to identify Best Available pollution control Technologies (BAT) for metal mining effluents. BAT has been defined as a combination of demonstrated treatment technologies and in-plant controls. In reviewing potential BAT level technology and technology trains (combinations of technologies that achieve a goal or goals) a set of "preferred" wastewater pollution control technology trains for the base metal, gold, iron, and uranium subsectors were identified. These technology trains are summarized below. Flow charts illustrating selected technology trains are presented in Appendix 3.

Base Metal Sector

Most base metal ores in Canada are separated using flotation, which is normally conducted in the pH 8 to 10 range. Hence, mill wastewater commonly requires pH control to lower the pH to the neutral range. Conversely, mine waters, untreated tailings pond effluents and waste rock pile drainage from base metal mines are commonly acidic due to the oxidation of sulphide minerals, and may also contain elevated concentrations of metals. This wastewater also requires pH control. Lime or other bases are added to neutralize the acidic solutions, and as a result of the neutralization most dissolved metals are removed from solution through precipitation as hydroxides.

Details of treatment of effluents from base metal mines are described in preferred technology trains presented in the BAT study. These technology trains, which provide control of pH, suspended solids and heavy metals in effluents arising in the base metal sector, are:

- Tailings Pond / Hydroxide Precipitation / Polishing Pond
- Tailings Pond / Hydroxide Precipitation / Clarification

- Tailings Pond / Sulphide Precipitation / Clarification
- Underwater Disposal

Tailings Ponds: tailings ponds provide containment for the deposition of mill slurry solids and metals that have precipitated out of solution as hydroxides and other solids. The rate of metal removal and subsequent deposition will depend on tailings pond physical characteristics, pH/alkalinity values, grind characteristics, the potential for acid mine drainage. Under favourable conditions tailings pond(s) alone may provide sufficient treatment to allow discharge of effluent to the environment. Otherwise, tailings ponds comprise an integral component of virtually all other treatment systems in all metal mining sectors.

Polishing Ponds: suspended solids in the form of fine tailings, rock or residual precipitates, are generally removed by gravity in polishing ponds. These ponds are commonly found in a series arrangement into which treated tailings water and mine water are discharged prior to recycle or final discharge to the environment. These ponds differ from tailings ponds primarily in size and in concentrations of influent solids. The size of the polishing pond required for satisfactory removal of suspended solids relies on such parameters as particle size, pH and temperature of the water, wind and wave effects, depth of water and inlet and outlet configurations.

Tailings Pond / Hydroxide Precipitation / Polishing Pond: in this technology the mill tailings are discharged into a tailings pond for primary solid/liquid separation. The overflow from the tailings pond is treated with lime to precipitate dissolved metals as hydroxides at a pH of 9 to 10. The treated effluent is then fed to a polishing pond for secondary solid/liquid separation to produce a final effluent which is discharged to the environment. The metal hydroxide sludges are returned to the tailings pond.

Tailings Pond / Hydroxide Precipitation / Clarification: this train incorporates sludge recycle to produce a high density sludge for disposal. The first stage in the train can equally be a tailings pond or polishing pond, in the case of acid mine water alone, for removal of suspended solids.

Tailings Pond / Sulphide Precipitation / Clarification: the solution in a tailings pond associated with base metal mines is most often neutral or alkaline as a consequence of the increased pH value usually inherent in the flotation processes. The neutral or alkaline pH level in the pond results in precipitation, to very high degree, of metal ions. This train incorporates precipitation of the residual dissolved metals as sulphides and two stages of clarification. The primary clarification is achieved in a Lamella plate clarifier while an active sand filter is used in the second polishing stage.

Underwater Disposal: underwater/unconfined disposal of tailings is not permitted under the *Metal Mining Liquid Effluent Regulations*. Under special *Fisheries Act* authorization this method of disposal for tailings containing sulphide minerals is practised at the Polaris Mine in the Northwest Territories and at the copper/zinc concentrator of Hudson Bay Mining and

Smelting at Snow Lake, in Manitoba. Underwater disposal reduces the oxygen access to the reactive sulphide minerals in the tailings, thereby curtailing the generation of AMD. The Mine Environment Neutral Drainage (MEND) Program is conducting extensive studies into the practicability and environmental aspects of this method.

Gold Sector

The main environmental concern in the gold mining subsector is the destruction of cyanide. To prevent adverse impacts on the environment the wastewater containing cyanide or cyanide compounds must be treated prior to discharge, in order to reduce the cyanide concentrations.

Preferred Technology Trains: the preferred technology trains which are effective in controlling suspended solids, pH, metals (Cu, Pb, Zn, Ni) and cyanide in the gold sector are:

- Natural Degradation (ND) (seasonal discharge with a two-pond system)
- INCO SO_2-Air (on slurry) / Tailings Pond / Polishing Pond
- ND / INCO SO_2-Air / Polishing Pond
- ND / Hydrogen Peroxide / Polishing Pond
- ND / INCO SO_2-Air / Clarification
- ND / Hydrogen Peroxide / Clarification

It is noted that natural degradation is used in a stand-alone or pre-treatment role on all but one of these trains. The exception is the train which includes treatment of mill tailings slurry (by the INCO SO_2-Air process) prior to solids removal in the tailings pond.

The additional control of arsenic and antimony in effluents is achieved by inclusion of a ferric ion precipitation step in each of the above trains.

Natural Degradation: natural degradation involves the removal of cyanide and metallocyanide complexes from wastewater by natural processes while the wastewater is retained for extended periods, usually in tailings ponds. The degradation of cyanide and metallocyanide complexes results from a combination of physical, chemical and biological processes including volatilization, chemical and photochemical decomposition, chemical and microbial oxidation, precipitation of metals, hydrolysis and adsorption onto solids.

INCO SO_2-Air: in the INCO SO_2 -Air process the cyanide component of metallocyanide complexes is selectively oxidized to cyanate by a mixture of SO_2 and air, in the presence of copper as a catalyst, in a controlled pH range. Iron, present as ferrocyanide, is not oxidized by the process, but is precipitated as a complex with the copper and zinc released from the cyanide complexes. Sulphur dioxide can be added as a gas, as sulphurous acid, or as a solution of sodium sulphite or sodium metabisulphite. The process has been applied to the treatment of both slurry and solution waste streams. The mill tailings, in the form of a slurry, are chemically treated before being pumped to the tailings pond (refer to Kilborn report for capital and operating costs).

Hydrogen Peroxide: this process is similar to the INCO SO_2-air process in that cyanide and metallocyanide complexes, except for iron cyanide, are oxidized to cyanate, often in the presence of copper as a catalyst and in a controlled pH range. The base metals copper, nickel and zinc, freed by oxidation of cyanide, form hydroxide precipitates. Ferrocyanide is precipitated by copper or zinc. Any excess hydrogen peroxide (H_2O_2) decomposes to water and oxygen. Hydrogen peroxide is added directly as a liquid normally at concentrations of 50 - 70% by weight. The process has been applied to both slurry and solution streams but appears to be more effective in clear solutions than in slurry.

ND / INCO SO_2-Air / Polishing Pond: the mill tailings are discharged directly into a tailings pond where natural degradation occurs prior to treatment using the INCO SO_2-Air process. Treated wastewater is sent to a polishing pond prior to discharge.

ND / Hydrogen Peroxide / Polishing Pond: this technology train is very similar to the ND / INCO SO_2-Air / Polishing Pond technology train, except that the hydrogen peroxide process is used instead of INCO SO_2-Air.

ND / INCO SO_2-Air / Clarification: a clarification step is substituted for a polishing pond in this technology train. The effluent from the oxidation process is treated in a reactor clarifier. The sludge recovered in the clarifier is returned to the tailings pond for disposal.

ND / Hydrogen Peroxide / Clarification: this technology train is the same as ND / INCO SO_2-Air / Clarification except that the INCO SO_2-Air step is replaced by the use of hydrogen peroxide.

Technologies In Limited Use: the BAT study also reviewed the following technologies for treating gold mill effluents. These technologies are currently in limited use and were not selected as "preferred technologies" in the report.

- alkaline chlorination
- Hemlo Gold process
- acidification - volatilization - regeneration (AVR)
- engineered wetlands

Alkaline Chlorination: a chemical treatment method that destroys cyanide (and cyanide complexes of copper, zinc, and nickel) by rapid oxidation with hypochlorite ions at pH values in the range of 10 to 11. The hypochlorite is provided by the reaction of chlorine gas with water or as sodium or calcium hypochlorite. The metals precipitate as hydroxides as the complexes are broken down. In mining in Canada this process has fallen into disuse since the emergence of the INCO SO_2-Air, hydrogen peroxide and Hemlo processes. It is still widely used in the metal finishing and plating industry and occasionally in gold mining areas outside Canada where partial treatment is acceptable.

Hemlo Gold Process: this is a patented process (Noranda Inc.) involving the addition of a premixed solution of $CuSO_4$ and $FeSO_4$ to the mill solution originating from the grinding circuit thickener and after recovery of contained gold by activated carbon in columns. The premixed solution is added at a controlled pH of approximately 9.5. Ferrous ion is oxidized to form ferric hydroxide, while cupric ions are simultaneously reduced to cuprous ions. The resulting cuprous ion removes free cyanide when required as an insoluble cuprous cyanide precipitate. Removing free cyanide subsequently results in the dissociation of copper, nickel and zinc cyanide complexes, leading to further removal of cyanide by cuprous ions. Copper, nickel, zinc, antimony and molybdenum are co-precipitated from solution with ferric sulphate addition and a solution pH of approximately 4.5. Lime is then added to increase the solution pH to 7.0 and hydrogen peroxide is added as required to remove residual cyanide. A reactor clarifier is employed to recover precipitate as sludge, which is pumped together with mill tailings slurry to the tailings pond. Final effluent is discharged to the environment.

Acidification - Volatilization - Regeneration (AVR): this process is based on the volatility of hydrogen cyanide resulting when slurry or solution is acidified. This acidified slurry/solution is then passed counter-current to a stream of air in a series of packed towers. The solution, stripped of hydrogen cyanide, is reneutralized with lime, and directed to waste. The effluent air stream containing the elevated hydrogen cyanide is directed upflow through a second series of packed columns counter-current to a lime or sodium hydroxide solution to produce regenerated cyanide solution for recycle. This process is effective for removing free cyanide, but is not effective for removing metallocyanide complexes. Also, scaling and other problems have been encountered such that its success to-date has been mixed.

Engineered Wetlands: plant materials can uptake heavy metals through their incorporation into tissue structures, and through surface adsorption. Metal removal is most effective during the growing period. Wetlands, particularly muskeg, also provide an effective filter for entraining suspended solids. The demarcation between engineered and naturally occurring wetlands is not always distinct. Frequently, natural wetlands are modified, using engineered structures (dykes, berms), to either enhance plant growth, or to manage flows. For example, Asarco's Sweetwater lead/zinc operation in Missouri and Canamax's gold mine in Northern Ontario. In northern climates, wetlands are most effective during the non-winter period. Two gold mills in northern Saskatchewan (Jolu and Cameco/Shore Gold) used this approach.

Iron Ore Sector

The beneficiation of iron ores involves physical and not chemical processes. Typical unit operations are gravity and magnetic separation and heavy media concentration.

Most processing operations are wet and the process effluents are discharged to tailings ponds. The recycle of water from the tailings ponds to the concentrator for re-use in the concentrator is maximized. In some instances, the tailings are thickened with the aid of flocculants/ coagulants (e.g. alum) prior to being pumped from the concentrator to the tailings pond.

Tailings ponds function as primary gravity settlers with any excess effluent reporting to a polishing pond before release to the environment.

The preferred technology trains in this sector are therefore considered to be:

- Tailings Pond / Polishing Pond
- Tailings Pond / Clarification

Uranium Sector

The single preferred technology train in this sector is:

- Hydroxide Precipitation / Tailings Pond / Radium Co-precipitation / Clarification / pH Adjustment / Monitoring Pond

The initial neutralization step is performed in the mill, usually on a single combined stream containing all effluents including solids tailings. This slurry is aerated to oxidize ferrous ions to ferric which are precipitated, along with other dissolved heavy metals, as hydroxides.

After this initial hydroxide precipitation step, the slurry is pumped to a tailings pond where separation of a liquid effluent takes place. The major contaminant in this effluent is the radionuclide, radium-226. Removal of dissolved radium is achieved by barium chloride addition to effect co-precipitation with barium sulphate ($BaRaSO_4$). Any dissolved arsenic is simultaneously precipitated as barium arsenate. The pH is controlled by lime during the course of these reactions. Any dissolved heavy metals present are also precipitated as hydroxides. The precipitates are recovered in a clarifier before disposal in a dedicated sludge pond. The pH of the clarifier overflow may require reduction to a achieve acceptable effluent standards and this is normally accomplished by the addition of sulphuric acid. The effluent flows to a monitoring pond from where it is discharged to the environment when it meets prescribed effluent quality standards.

2.5 Mine Closure

Mines are closed when the ore minerals are completely exhausted, or when it is no longer profitable to recover those minerals which remain.

In the past, mines were often abandoned without reclamation of the area or stabilization of the mine wastes. Such abandoned mines are found in many areas of Canada. Some of the best known examples are the Waite Amulet Mine in Quebec, and the Mt. Washington Mine in British Columbia, both of which are now being reclaimed.

Modern site decommissioning procedures are designed to prevent many of these problems so frequent at older mines. After shutdown, underground workings are capped to limit the flow of minewater from them. Open pits are allowed to fill with water. Buildings on the site are dismantled, and utility lines into the site are removed, and roads to the site may be dug up . Oil and fuel spills around vehicle storage and maintenance areas are remediated. The site, as well as road and utility corridors to it, may be revegetated.

Tailings and waste rock require special attention, since they could continue to pose significant environmental hazards after the site is abandoned. The question of how to decommission tailings and waste rock, so that ongoing treatment after closure is not required, is the main focus of the Mine Environment Neutral Drainage (MEND) research program. The key to all options is limiting the amount of oxygen coming in contact with the acid generating material, since without oxygen, acid will not be produced. The main AMD abatement and prevention strategies under study include:

- the use of impermeable barriers to cap tailings and waste rock. This reduces the infiltration of water into the waste, and limits or eliminates the acid generation.

- underwater disposal. If the waste material is kept wet, oxidation will be limited since the material will be exposed to less oxygen. If the waste is deposited in deep, anoxic water, oxidation can be completely eliminated.

- treating effluent in wetlands. Wetlands are reducing environments, and within them live bacteria capable of reducing sulphates to sulphides, raising the pH, and causing the metals to precipitate out of solution.

While none of these options are ideal, given the current state of knowledge, the only alternative is to treat the acidic drainage in perpetuity, prior to the discharge of effluents into the environment.

3 The Regulatory Regime

3.1 Development and Implementation of the MMLER

3.1.1 The *Fisheries Act*

The *Fisheries Act* is one of the first major pieces of legislation passed by the Canadian Parliament, in 1868. The basic framework for the existing regulatory approach to pollution prevention was introduced by amendments to the Act in 1970. Additional improvements to this framework were passed in 1977, 1985 and 1991. The *Metal Mining Liquid Effluent Regulations* (MMLER) are based on the following key pollution provisions of the Act:

- Subsection 36(3): prohibits the deposit of all deleterious substances into waters frequented by fish. This general prohibition applies to everyone anywhere in Canada.
- Subsection 36(4): provides for exceptions to this general prohibition by or under regulations.
- Subsection 36(5): provides for the authority to make regulations (such as the MMLER) to specific allowable deposits of deleterious substances.
- Subsection 34(1): contains definitions, including the definition of 'deleterious substance' and the power in subsection 34(2) to make regulations prescribing specific deleterious substances.

In addition, the Act contains other provisions related to implementation of pollution prevention, inspections, enforcement and civil remedies in Sections 37 to 42 and Sections 78.1 to 79.6.

The fish habitat protection provisions (Section 35) are also relevant to mining operations. Subsection 35(1) generally prohibits the destruction or harmful alternation or disruption of fish habitat. Subsection (35(2) provides for the issuance of authorizations for habitat alteration, disruption or destruction that would otherwise be prohibited.

Part IX of the *Fisheries General Regulations* (S.O.R./93-53; 4 February 1993) provides administrative procedures for requesting authorization to alter fish habitat. The Regulations are administered according to site specific needs, and do not contain numerical standards as do the MMLER.

In developing or operating a mine (particularly the construction of new tailings impoundment areas), some disruption of habitat may occur. Approval of such disruption is required under Subsection 35(2) of the Act or under Subsection 5(2) of the MMLER in the case of new tailings impoundment areas for metal mines that are subject to the MMLER.

3.1.2 Regulatory Approach

The current *Metal Mining Liquid Effluent Regulations* (MMLER) were developed between 1973 and 1977 with input from a federal-provincial-industry task force. The task force considered the concentrations that can be technologically achieved for various metals through the application of Best Practicable Technology (BPT) based upon the physical/ chemical properties of these metals contained as solids and in solution, in Canadian mine and mill waste waters.

In developing the MMLER the Task Force through its 'Working Groups' addressed the mining industry's three basic water pollution issues:

1) reduction and control of solids in mine water, surface run off and tailings pond discharges;

2) reduction and control of dissolved metals (arsenic, copper, nickel, lead and zinc) and acidity (low pH) in mine waters and tailings pond discharges; and

3) reduction and control of radium-226 in uranium mine and mill effluents and tailings pond discharges.

The numerical standards developed by the task force addressed these three issues and are incorporated into Schedule I of the MMLER. These **national baseline standards** were intended to provide adequate protection for fish and aquatic life. If necessary, more stringent federal standards could be prescribed by a site-specific regulation. (None have been developed to date).

Accordingly, the concentration of these metals in mine/mill effluents can be reduced to levels in the range of 0.2 to 0.5 mg/L by chemical precipitation through pH control and physical settling in waste water treatment plants or tailings ponds. While this is a 'technology based' approach to water pollution control, careful consideration was also given to evaluating the level of fish protection that would be provided through the application of the best practicable technology.

3.1.3 *Metal Mining Liquid Effluent Regulations*

The *Metal Mining Liquid Effluent Regulations* were promulgated under the *Fisheries Act* in February 1977, and apply to new, reopened or expanded base metal, iron ore and uranium mines. The regulations set specific authorized concentration limits for deleterious substances in effluents discharged to waters frequented by fish (see Table 7). The concentration limits are 'technology based', with the best practicable technology (BPT) being achieved through recognition and utilization of the constant physical/chemical properties of the metals; arsenic, copper, lead, nickel and zinc and radium-226. The numerical standards in the current regulations are comparable to standards recently developed by other jurisdictions (e.g. Ontario which under its Municipal Industrial Strategy for Abatement (MISA) program, published new effluent limits in September 1994).

Table 7: Authorized levels of deleterious substances prescribed in the *Metal Mining Liquid Effluent Regulations*

Part 1: Authorized levels of substances

Substance	Max. Authorized Monthly Arithmetic Mean Concentration (mg/L)	Max. Authorized Concentration in a Composite Sample (mg/L)	Max. Authorized Concentration in a Grab Sample (mg/L)
Arsenic	0.5	0.75	1.0
Copper	0.3	0.45	0.6
Lead	0.2	0.3	0.4
Nickel	0.5	0.75	1.0
Zinc	0.5	0.75	1.0
Total Suspended Matter (TSM)	25.0	37.5	50.0
Radium-226	10.0 pCi/L	20.0 pCi/L	30.0 pCi/L

Note: The concentrations are given as total values with the exception of radium-226 which is a dissolved value after filtration of the sample through a 3 micron filter.

Note: The **acceptable** levels of substances in the *Metal Mining Liquid Effluent Guidelines* have the same numerical values as the **authorized** levels of deleterious substances prescribed in the *Metal Mining Liquid Effluent Regulations*.

*Note: TSM - Total Suspended Matter may also be referred to as total Suspended Solids by Other Jurisdiction.

Part 2: Authorized levels of pH

Min. Authorized Monthly Arithmetic Mean	Min. Authorized pH in a Composite Sample	Min. Authorized pH in a Grab Sample
6.0	5.5	5.0

For the purposes of the regulations, effluents are considered to be mine water effluent, mill process effluent, tailings impoundment area effluent, treatment pond or treatment facility effluent, as well as seepage and surface drainage from the site. Operators are required to measure or estimate the volume or effluent discharged, but the regulations do not control contaminant loading in the receiving environment.

The regulations do not apply to gold mines as defined by the regulation. For the purpose of the MMLER, a gold mine is any mine where the gold produced from the mine in recovered at the site by cyanidation and accounts for more than 50% of the value of mine output.

3.1.4 Metal Mining Liquid Effluent Guidelines

The 1970 pollution provisions of the *Fisheries Act* did not provide authority to make flexible regulations for gradually phasing in regulatory requirements for existing mines. Subsequent amendments provide broader and more flexible authority to make regulations.

The Metal Mining Liquid Effluent Guidelines were published at the same time as the MMLER to establish effluent quality objectives for existing metal mines, other than gold mines using cyanidation process, that had commenced operation before February 25, 1977. The acceptable levels for substances in the Guidelines have the same numerical values as the authorized levels of substances prescribed in the MMLER.

Effluent quality objectives are not legally enforceable for these mines, but their operations are subject to the general provisions of the *Fisheries Act*. Compliance with the guidelines is considered to meet the spirit of the law, but the discharge of an effluent that is acutely lethal to fish may be an offence under Subsection 36(3) of the *Fisheries Act*. A mine may be legally obligated to meet the guidelines if a federal, territorial, or provincial government agency imposes these limits in a regulation, permit or licence issued under its legislation.

3.1.5 Guidelines for Acute Lethality Measurement

Environment Canada developed Guidelines for the Measurement of Acute Lethality in Liquid Effluents from Metal Mines which specify a bioassay test procedure in which fish (rainbow trout) are exposed to undiluted effluent for 96 hours. If 50% of the fish survive, then the effluent is considered to pass the test.

The Regulations, Guidelines and an Environmental Code of practice for mines are published in: Environment Canada Report EPS-1-WP-77-1. The testing methods contained in EPS 1/RM/13 - 1990 and EPS//RM/9 - 1990.

3.1.6 Consideration of Gold Mine and Mill Effluents

In the mid-1970's, there were no commercially proven treatment methods for the control of cyanide bearing liquid and solid wastes from gold mines. Untreated cyanide bearing gold mine effluents are generally very toxic to fish. Environment Canada decided in 1977 to **exclude** gold mines using cyanidation from the application of the MMLER. Instead, a gold mining working group was set up as part of the Task Force to encourage and promote technologies for the control of cyanide. During the late 1970's and early 1980's, Canada became a world leader in developing and implementing several technologies, including alkaline chlorination, the Inco SO_2/air oxidation process, hydrogen peroxide oxidation, cyanide regeneration and optimization of natural degradation in tailings impoundments (see Section 2.3). In some instances, effluents from natural degradation systems are subsequently subjected to one or more of the aforementioned treatment technologies in order to meet standards prescribed by other regulatory agencies.

All of the approximately 50 Canadian gold mine effluents are subject to limits specified in provincial regulations, permits, licences and territorial Water Board licenses.

3.1.7 The *Fisheries Act* and the *Canadian Environmental Protection Act*

The *Canadian Environmental Protection Act* (CEPA) came into force in June 1988. Part II of CEPA deals with toxic substances and provides authority to add toxic substances to a schedule (Sec. 33) and to make regulations (Subsection 34(1)) to control toxic substances on that schedule. Some substances regulated under the MMLER were previously declared toxic (lead) under earlier legislation or have been found to be "toxic" as defined by CEPA (arsenic and nickel) in the course of the assessment of 44 substances on the Priority Substances List (PSL).

Subsection 34(3) of CEPA however, provides that regulations are **not** to be made under

Subsection 34(1) of CEPA if the substance is already regulated under another Act of Parliament (including the *Fisheries Act*). The review of the MMLER will therefore examine issues from the point of view of the *Fisheries Act* only and not CEPA.

3.1.8 Industry's Compliance Performance

Compliance is assessed on the basis of monthly effluent quality data and standards. A mine is considered to be in compliance for a given month if all liquid effluent discharges meet prescribed standards for the eight effluent quality parameters in the MMLER for that month. Compliance for the year is based on the percentage of operational months for which a mine was in compliance.

In 1990, 29 of the 49 regulated mines achieved 100% compliance and the overall rate of compliance was 87.1%. Of the 52 guideline mines, to achieved 100% compliance while the overall rate of compliance with the Guidelines Standards was 82%. It should be noted that three of the 52 guideline mines practise unconfined tailings disposal by placing tailings in natural water bodies rather than in engineered tailings impoundments. This practice is permitted by special authorizations issued by provincial agencies prior to 1977.

Table 8 provides a summary of the level of compliance by the mines under regulation from 1982 to 1990. Although the mines are shown to have achieved 95.2% compliance in 1982, complete effluent quality data were not available for all of the 20 regulated mines at that time.

Table 9 provides a summary of compliance status of the regulated mines that were out of compliance for 3 or more months in 1990 and the measures taken by the operators to improve their compliance status by 1991.

The most recent compliance status of the industry may be obtained through reference to Status Report of Water Pollution Control in the Canadian Metal Mining Industry (1990 and 1991) -- Environment Canada Report EPS-1/MM/4 December 1992.

Table 8: Mines under MMLER: Summary of compliance by mines under regulations in 1982, 1986 and 1990 (note that 1982 data were incomplete)

Year	No. of Mines	% Compliance
1982	20	95
1986	30	84
1990	49	87

Table 9: Mines under MMLER: Summary of compliance status for 1990 and 1991 for mines out of compliance for 3 or more months in 1990

Name	Province	Months out of compliance	% Compliance 1990	% Compliance 1991	Comments
A	B.C.	3	62.5	-	Closed Sept. 1990
B	B.C.	3	75.0	91.7	Treatment system modified
C	Manitoba	5	58.3	100.	Treatment system on line, mid 1990
D	Ontario	5	58.3	71.4	Increased pH monitoring commenced Feb. 1991
E	Ontario	3	75.0	91.7	Increased treatment area retention time
F	Quebec	4	66.7	66.7	Pond expanded to increase retention time
G	Quebec	9	25.0	58.3	Flocculation plant added, June 1991
H	Quebec	3	75.0	100	Automated lime addition system installed in late 1990
I	Quebec	3	25.0	100	---
J	Quebec	3	75	58.3	Modifications planned for the waste water management system
K	Quebec	11	8.3	58.3	Storage pond, polishing pond and lime plant added in 1991
L	N.B.	4	60	--	Operations suspended, Oct. 1990

3.2 Effluent Regulatory Limits of other Jurisdictions

3.2.1 Domestic

In reviewing the regulatory regimes applicable to Canadian mine effluents, it is essential to consider the regulatory limits established for mine/mill effluents by provincial and territorial authorities. As noted in Section 1.2 the limits contained in the MMLER are considered to be national baseline standards. Other jurisdictions are free to set more stringent limits as well as to include additional parameters (*e.g.* cyanide, molybdenum, cadmium, ammonia, mercury, *etc.*). In such cases, the mines must comply with the more stringent limits.

Ontario

The Ontario Ministry of Environment and Energy (OMOEE) prescribes effluent quality limits in Certificates of Approval issued to individual mines, on a site specific basis. The limits found in these certificates are influenced by the nature of the receiving waters at the site and by existing guidelines or regulations that apply to the industry. In general, the effluent quality limits prescribed in existing certificates of approval are equal to, or more stringent than, those in the MMLER.

In September, 1994 the Government of Ontario released new effluent limit regulations for metal mining. The effluent limits given in the regulation are independent of the site specific limits stated in certificates of approval.

The limits for substances in the regulation are the same as those in the MMLER for: arsenic, copper, nickel, lead and zinc. The limits for total suspended matter (15 mg/L) and pH (with lower and upper limits of 6.0 and 9.5) are more stringent than those prescribed by the MMLER. Further, as the regulations apply to gold mines, they also specify a limit of 1.0 mg/L for total cyanide. The regulations also require that all process effluents produced by the Ontario metal mining industry be non-toxic to rainbow trout and *Daphnia magna*. Effluent by-passes are prohibited.

Quebec

The Quebec Ministry of the Environment issued Directive 019 in October 1989. This directive, which applies to all metal mines, addresses the environmental and permitting aspects of all phases of mining from exploration to production, waste management and close out. The directive requires that final effluents meet the same concentration limits as the MMLER for arsenic, copper, lead, nickel, zinc and TSM. Directive 019 also contains the following limits: 3.0 mg/L total iron, 1.5 mg/L total cyanide, and 0.1 mg/L free cyanide, as well as the requirement that the effluent be non acutely lethal and that its pH be in the range of 6.5 to 9.5.

British Columbia

British Columbia issued: Pollution Control Objectives for the Mining, Smelting and Related Industries, under the *Pollution Control Act* in 1979. These objectives address both effluents and air emissions. The effluent objectives contain recommended ranges of dissolved elements and compounds contained in final effluents discharged to marine or fresh water. The province issues Effluent Discharge Permits setting effluent limits on a site specific basis, to mines discharging to natural receiving waters.[1] The final effluent limit numbers embodied in an Effluent Discharge Permit for a mine are established based upon such factors as:

- the sensitivity of the receiving water
- seasonal water flows
- the efficiency of the existing or proposed treatment technology

Other Canadian Jurisdictions

The provinces of Manitoba, Nova Scotia and New Brunswick require the mines to meet the effluent limits contained in the federal *Metal Mining Liquid Effluent Guidelines*.

In the Yukon and Northwest Territories, site specific mine effluent limits are set in water licences issued under the Territorial Water Boards under the authority of the federal Department of Indian Affairs and Northern Development.

The provincial effluent limits are presented in Table 10.

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[1] 6 of the 15 British Columbia metal mines with tailings impoundments do not discharge effluents.

Table 10: Canadian effluent limits (after Kilborn 1991)

Parameter mg/L	Ontario Monthly mean	Quebec Monthly mean	B.C. Range ***	Sask.		Nfld	Canada*		
				Mean	Max		Monthly mean	Composite sample	Grab sample
Cadmium	0.001**		0.01-0.1			0.05			
Mercury	0.001**		Nil-0.005			0.005			
Suspended solids	15	15	25.0	25 - 75		30	25.0	37.5	50.0
pH	6.0 - 9.5**	6.5 - 9.5	6.5-8.5 6.5-10	6.0-9.5	5.0-10.0	5.5-9.0	>6.0	>5.5	>5.0
Aluminum			0.5 - 1.0						
Arsenic, total	0.5**	0.50	0.10 - 1.0	0.5	1.0	0.5	0.5	0.75	1.0
Arsenic, trivalent			0.05- 0.25						
Copper	0.3**	0.30	0.05 - 0.03	0.3	0.6	0.3	0.3	0.45	0.6
Nickel	0.5**	0.50	0.2 - 1.0	0.5	1.0	0.5	0.5	0.75	1.0
Lead	0.2**	0.20	0.05 - 0.2	0.2	0.4	0.2	0.2	0.3	0.4
Zinc	0.5**	0.50	0.2 - 1.0	0.5	1.0		0.5	0.75	1.0
Iron		3.00	0.3 - 1.0						
Antimony			0.25 - 1.0						
Chromium			0.05 - 0.3						
Cobalt			0.5 - 1.0						
Fluorine			2.5 - 10.0						
Manganese			0.1 - 1.0						
Molybdenum			0.5 - 5.0						
Selenium			0.05 - 0.5						
Silver			0.05 - 0.5						
Gross Alpha			10 - 100						
Uranium Dioxide	0.001**		2.0 - 5.0						
Uranium				2.5	5.0				
Radium-226 Bq/L pCi/L			Less than 10.0	0.37	1.11	0.37	10pCi/L	20pCi/L	30pCi/L
Thorium-230 Bq/L				1.85	3.7				
Lead-210 Bq/L			0.92	1.84					

Table 10: Canadian Effluent Limits (continued)

Parameter mg/L	Ontario Monthly mean	Quebec Monthly mean	B.C. Range ***	Sask.		Nfld	Canada*		
				Mean	Max.		Monthly mean	Composite sample	Grab sample
Nitrite/Nitrate as nitrogen			10.0 - 25.0						
Ammonia as nitrogen	10.0**								
Unionized Ammonia				0.5	1.0				
Temperature						>32 C			
Strontium-90		3.00	0.3 - 1.0			0.37			
Oils (either extract)			0.25 - 1.0			15			
Oil & grease			0.05 - 0.3			10.0-15.0			
Barium			-			5.0			
Boron			-			5.0			
Chlorine			0.5 - 1.0			1.0			
Phosphorus	1.0**								
Phosphate as phosphorus			2.0 - 10.0						
Total Cyanide	(1.0)**	1.50	0.1-0.5	1.0	2.0	0.025			
Free Cyanide		0.10							
Phenols	0.02**	0.10							
Biological Oxygen Demand	15**								
Dissolved Solids			2500 - 5000		1000				
Toxicity	(non-toxic)		80% - 100%						

* Federal guidelines used by Manitoba, Nova Scotia and New Brunswick

** Typical values more recently applied on Certificates of Approval (OWRA Section 24) in Ontario.

*** Lower limits are for new plants, and plants discharging to sensitive receiving environments higher limits are for plants, discharging to a non sensitive receiving environment limits are guidelines as opposed to regulations site specific water quality objectives determine the limits specified in a permit. The permit limits may be more stringent.

(1) Ontario Metal Mine Effluent Regulation Limits under MISA.

(2) Effluent must be non-toxic to rainbow trout and *Daphnia magna*.

3.2.2 International Effluent Limits

In considering the Canadian metal mine effluent regulatory regime, it is also useful to compare the MMLER limits with those set by major metal mining nations. The concentration limits for potential pollutants contained in mine/mill effluents discharged to the environment in the United States, Germany, Sweden, Finland, Italy, Spain, Tasmania (Australia), Brazil, Chile, Mexico, Indonesia, Papua New Guinea and the Philippines are presented in Tables 11 and 12.

As Canada has entered the North American Free Trade Agreement, it should be noted that NAFTA is one of the major factors causing Mexico to revitalise its environmental protection program. It has passed a General Law of Ecological Equilibrium and Environmental Protection. Environmental compliance is administered by the National Institute of Ecology (standards, assessments, etc.) and the Office of the Attorney General for the Protection of the Environment. The National Water Commission also assists in the regulation of water use. Effluent standards to protect water quality were promulgated in 1989 and are comparable to US and Canadian criteria (see Table 12). At present, there are ongoing discussions among Secretariat of Social Development (SEDOSOL), Secretaria de Energia, Minas & Industria Paraestatol and Camara Minera de Mexico to establish environmental limits for the Mexican Mining industry. (ADI Limited for Environment Canada, March 1994).

Table 11a: U.S. effluent regulations for copper, lead, zinc, gold, silver and molybdenum ores (after Kilborn 1991)

Parameter mg/L	1		2		3		4		5		6		7		8		9	
	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg
Total suspended solids	30	20	30	20	30	20	50	30	30	20							30	20
pH	6.0	9.0	6.0	9.0	6.0	9.0	6.0	9.0	6.0	9.0	6.0	9.0					6.0	9.0
Cadmium			0.10	0.05	0.10	0.05			0.10	0.05	0.10	0.05	0.10	0.05	0.10	0.05	0.10	0.05
Copper	0.30	0.15	0.30	0.15	0.30	0.15			0.30	0.15	0.30	0.15	0.30	0.15	0.30	0.15	0.30	0.15
Zinc	1.5	0.75	1.0	0.5	1.0	0.5			1.0	0.5	1.0	0.5	1.5	0.75	1.0	0.5	1.5	0.75
Lead	0.6	0.3	0.6	0.3	0.6	0.3							0.6	0.3	0.6	0.3	0.6	0.3
Arsenic					1.0	0.5			1.0	0.5	1.0	0.5						
Mercury	0.002	.001	0.002	.001									0.002	.001	0.002	.001	0.002	.001

Best Practical Control Technology (BPT):

(1) Concentration of pollutants discharged in mine drainage for copper, lead, zinc, gold and silver ores.

(2) Concentration of pollutants discharged from mills which employ froth flotation for copper, lead, zinc, gold and silver ores.

(3) Concentration of pollutants in mine drainage from mines producing 5,000 metric tons or more of molybdenum ores per year.

(4) Concentration of pollutants in mine drainage from mines or mills producing less than 5,000 metric tons of molybdenum ores per year by methods other than ore leaching.

(5) Concentration of pollutants discharged from mills processing 5,000 tons or more of molybdenum ore per year by purely physical methods including ore crushing, washing, jigging and heavy media separation.

(6) Concentration of pollutants discharged from mills processing 5,000 metric tons or more of molybdenum ores per year by froth flotation methods.

Best Available Technology Economically Achievable (BAT):

(7) Concentration of pollutants discharged in mine drainage for copper, lead, zinc, gold and silver ores.

(8) Concentration of pollutants discharged from mills which employ froth flotation for copper, lead, zinc, gold, silver, or molybdenum ores.

New Source Performance Standards - Best Available Demonstrated Technology (BADT):

(9) Concentration of pollutants discharged in mine drainage from mines producing copper, lead, zinc, gold, silver, or molybdenum ores.

Table 11b: U.S. effluent regulations for iron, uranium and nickel ores (after Kilborn 1991)

Parameter mg/L	Iron		Uranium 1		Uranium 2		Uranium 6		Uranium 7		Nickel 3		Nickel 4		Nickel 5	
	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg	Max	Avg
Total suspended solids	30	20	30	20	30	20			30	20	30	20	50	30	30	20
pH	2.0	1.0														
Iron, dissolved	6.0	9.0	6.0	9.0	6.0	9.0			6.0	9.0	6.0	9.0	6.0	9.0	6.0	9.0
Cadmium											0.10	0.05			0.10	0.05
Copper											0.30	0.15			0.30	0.15
Zinc			1.0	0.5	1.0	0.5	1.0	0.5	1.0	0.5	1.0	0.5			1.0	0.5
Lead											0.6	0.3				
Arsenic					1.0	0.5					1.0	0.5			1.0	0.5
Chemical Oxygen Demand			200	100	500		200	100	200	100						
Radium-226, dissolved			10	3	10	3	10.0	3.0	10.0	3.0						
Radium-226, total			30	10	30	10	30.0	10.0	30.0	10.0						
Uranium			4	2			4.0	2.0	4.0	2.0						
Ammonia					100											

Best Practical Control Technology (BPT):

(1) Concentration of pollutants discharged in mine drainage for uranium, radium and vanadium ores.

(2) Concentration of pollutants discharged from mills which employ the acid leach, alkaline leach or combined leach process for the extraction of uranium, radium and vanadium ores.

(3) Concentration of pollutants in mine drainage from mines producing 5000 metric tons or more of nickel ores per year.

(4) Concentration of pollutants in mine drainage from mines producing less than 5000 metric tons of nickel ore per year by methods other than ore leaching.

(5) a: Concentration of pollutants discharged from mills processing 5000 metric tons or more of nickel ore per year by purely physical methods including ore crushing, washing, jigging and heavy media separation and magnetic and electrostatic separation.

b: Concentration of pollutants discharged from mills processing 5000 metric tons or more of nickel ore per year by froth flotation method.

Best Available Technology Economically Achievable (BAT):

(6) Concentration of pollutants discharged in mine drainage from mines that produce uranium ore including plants using in-situ leach methods.

New Source Performance Standards - Best Available Demonstrated Technology (BADT):

(7) Concentration of pollutants discharged in mine drainage from mines that produce uranium ore excluding mines using in-situ leach methods.

Table 12: International effluent limits (after Kilborn 1991)

Para-meter	**Canada**			**Germany**	**Sweden (1)**	**Finland (2)**	**Italy**	**Spain (3)**		
mg/L	Monthly mean	Composite samples	Grab sample					**1**	**2**	**3**
Total Susp. Solids	25	37.5	50	-	15	10-60	80	300	150	80
pH	>6.0	>5.5	>5.0	-	-	5.5-9.5	5.5-9.5	-	5.5-9.5	-
Arsenic	0.50	0.75	1.0	0.10	-	-	0.50	1.0	0.50	0.50
Cadmium	-	-	-	0.20	-	-	0.02	0.50	0.20	0.10
Cyanide (total)	-	-	-	-	-	0.50	0.50	-	-	-
Chromium	-	-	-	0.50	-	-	0.20	-	-	-
Copper	0.30	0.45	0.60	0.50	0.10	0.05-3.0	0.10	10	0.50	0.20
Mercury	-	-	-	0.05	-	-	0.005	-	-	-
Nitrogen - Ammonia	-	-	-	-	-	-	-	50	50	15
Nickel	0.5	0.75	1.0	-	0.10	0.30-1.0	2.0	10	3.0	2.0
Lead	0.20	0.30	0.40	0.50	0.10	-	0.20	0.50	0.20	0.20
Zinc	-	-	-	1.0	-	-	0.005	20	10	3

Notes:

[1] Guidelines - each operation is assessed on a case by case basis.

[2] Range of discharge approval limits in effect at six metal mines.

[3] In Spain the limits are divided into three categories; 1, 2, and 3, with decreasing concentrations.

- No limit has been established

Varying QA/QC procedures are employed by different countries

Table 12: International effluent limits (continued)

Parameter mg/L	Tasmania		Brazil		Chile		Mexico	Indonesia			Papua New Guinea		Philippines	
	FW	Marine	1	2	3	4	5	6	7	8	FW	Marine	FW	Marine
Total susp. solids	-	-	1.0	-	300	100	*	1000	1000	100	-	-	70	150
pH	-	-	5.0-9.0	6.0-9.0	5.5-9.9	5.5-9.9	**	6.5-8.5	5.0-9.0	6.0-9.0	***	***	6.5-9.0	6.0-9.0
Arsenic	0.05	0.25	0.50	0.005	0.50	0.50	0.20	0.05	0.05	1.0	0.05	0.05	0.20	0.50
Cadmium	0.01	0.01	0.20	0.001	0.50	0.30	0.001+	0.01	0.01	0.01	0.01	0.01	0.05	0.10
Cyanide	0.05	0.20	-	-	1.0	1.0	0.005	0.10	0.10	0.02	0.005	0.01	0.20	0.20
Chromium	0.05	0.05	0.50	0.05	0.50	0.50	-	-	-	-	-	-	0.10	0.20
Copper	1.0	1.0	10	0.02	3.0	3.0	0.012	1.0	1.0	0.02	1.0	0.03	-	-
Mercury	0.002	0.002	-	-	0.02	0.02	.00001	0.001	.0002	.0002	0.002	.0002	.0005	0.005
Nitrogen, Total	0.50	0.50	-	-	80	10	-	-	-	-	****	****	-	-
Nickel	-	-	-	-	4.0	3.0	0.158+	-	-	-	1	1	-	-
Lead	0.05	2.0	0.50	0.03	1.0	1.0	0.058+	0.05	0.10	0.03	0.005	0.004	0.30	0.50
Zinc	0.002	0.002	5.0	0.18	5.0	5.0	0.11	5.0	5.0	0.02	5.0	5.0	-	-

Notes:

FW Fresh Water

1 Effluent Standard (most States have their own standards, but they often duplicate the Federal Standards).

2 Ambient Standard (Even if effluents comply with effluent standards, discharges are not allowed if the concentration of any parameter in the receiving waters exceeds those established by these regulations.

3 Discharge into sewer systems.

4 Discharge into waterways.

5 Drinking water guidelines.

6 discharge to water bodies that can be used as drinking water without treatment.

7 Discharge to water that can be used for the production of drinking water.

8 discharge to waters that can be used for fisheries and aquaculture.

+ Values dependent on hardness, value is for 100 mg/L $CaCO_3$.

* pH cannot vary more than 0.2 pH units from natural values

** In combination with colour values, it cannot reduce photosynthesis more than 10% from natural values.

*** No alteration to natural levels.

**** Maximum permitted concentrations of ammonia nitrogen vary from 16.1 mg/L at pH = 7.0 and temperature = 5 °C to 0.04 mg/L at pH = 9.0 and temperature = 35 C

Varying QA/QC procedures are employed by different countries

Glossary

Absorption: Chemical definition: penetration of one substance into the body of another. Biological definition: the act of absorbing, i.e., to take in as fluids or gases through a cell membrane. To take a substance (e.g., water, nutrients) into the body through the skin or mucous membranes, or in plants, through root hairs.

Acanthite: a silver sulphide mineral [Ag_2S].

Acclimation: (1) steady state compensatory adjustments by an organism to the alteration of environmental conditions. Adjustments can be behavioural or physiological/biochemical. (2) An adaptation of aquatic organisms to some selected experimental conditions, including adverse stimuli.

Acid: a substance containing hydrogen which, dissolved in water, tends to provide hydrogen ions (protons); or a substance having a tendency to lose protons.

Acid Extractable Metal: the concentration of a metal in solution after treatment of an unfiltered sample with dilute mineral acid, cold or hot.

Acidity: the quantitative capacity of aqueous media to react with hydroxyl ions; a measure of water's ability to neutralize a base.

Acid Mine Drainage: low pH drainage water from certain mines. The low pH is usually caused by the oxidation of sulphide minerals to sulphuric acid. Mine drainage can also contain high concentrations of metals.

Acute Toxicity: within a short period of time which is not usually a significant portion of the lifespan, e.g. ≤ 4 days for fish. An acute, toxic effect would be induced and observable within a short period.

Adsorption: the retention of gases, dissolved materials, or ions on the surface of solid particles, including organisms and substrates.

Alevin: a recently-hatched, non-feeding fish with an evident yolk sac (for nutritive requirements). Often referred to as yolk-sac fry.

Algae: comparatively simple chlorophyll-bearing plants, most of which are aquatic and microscopic in size.

Alkalinity: a measure of a water's capacity to neutralize an acid. It indicates the presence of carbonates, bicarbonates and hydroxides, and, less significantly, borates, silicates, phosphates and organic substances. It is expressed in milligrams of $CaCO_3$ per litre.

Amphipod: any crustacean belonging to the order Amphipoda, a group of small, shrimp like aquatic animals. Many amphipods are benthic, and feed on algae and detritus.

Annelid: ringed or segmented worms, including aquatic and terrestrial worms such as leaches and earthworms

Antagonistic: an interaction between two potential toxins in which the combined effect of the toxins is less than the effect of either toxin alone would have been.

Anthropogenic: created by humans.

Apatite: a group of phosphate minerals. The most common apatite minerals are fluorapatite $[Ca_5(PO_4)_3F]$ and chlorapatite $[Ca_5(PO_4)_3Cl]$.

Arsenide Mineral: a metallic mineral characterized by the covalent bonding of arsenic with a metal such as iron, nickel or cobalt. An example of an arsenide mineral is niccolite, which has the chemical formula NiAs.

Arsenides: see "Arsenide Minerals"

Arsenopyrite: an iron sulpharsenide mineral [FeAsS]. It is the most common arsenic mineral, and commonly occurs in association with gold.

Arsine Gas: hydrogen arsenide $[AsH_3]$, a volatile gas.

Arthropod: an animal of the phylum *Arthropoda*. This phylum includes over a million species, including insects and crustaceans. Arthropods are invertebrate animals with hard, jointed exoskeletons, paired, jointed legs, and segmented bodies. The phylum includes terrestrial and aquatic animals such as crabs, lobsters, insects, spiders, and centipedes.

Avoidance Behaviour: s response of a fish or other organism to the presence of a contaminant or other stimulus, whereby the animal actively moves away from the source.

Barite: a barium sulphate mineral $[BaSO_4]$.

Base: a substance which, dissolved in water, tends to provide hydroxide ions; or a substance having a tendancy to accept protons.

Base Metal: chemically active metals. In mining, the key base metals are Cu, Pb, Zn, Ni, and Mo.

Baseline Study: a study designed to document existing environmental conditions at a given site. The results of a baseline study may be used to document temporal changes at a site or document background conditions for comparison with another site.

Beneficiation: improving the chemical or physical properties of raw ore so that the metal can be recovered at a profit.

Benthic: refers to organisms living at the bottoms of water bodies (marine or freshwater). Benthic organisms may live in or on the bottom sediment, or be attached to rocks.

Benthic Invertebrates: those animals without backbones living on and/or in the bottom of a water body.

Bioaccumulation: general term describing a process by which chemicals are taken up by aquatic organisms from water directly or through consumption of food containing the chemicals.

Bioassay: a laboratory test used to evaluate the toxicity of a material (commonly sediments or wastewater) by measuring behavioral, physiological, or lethal responses of organisms.

Bioavailable: that portion of a chemical, compound or element that can be taken up readily by living organisms.

Bioconcentration: a process by which there is a net accumulation of a chemical directly from water into aquatic organisms resulting from simultaneous uptake (e.g., by gill or epithelial tissue) and elimination.

Bioconcentration Factor (BCF): a unitless value describing the degree to which a chemical can be concentrated in the tissues of an organism in the aquatic environment. An apparent equilibrium during the uptake phase of a bioconcentration test, the BCF is the concentration of a chemical in one or more tissues of the aquatic organisms divided by the average exposure concentration in the test.

Biological Oxygen Demand (BOD): measure of oxygen depletion of water due to bacterial decay of organic pollutants. Gives an indication of how much organic matter is in the water.

Bioluminescence: a phenomenon of light emitted from living organisms as a result of their biochemical activities, usually enzymatic.

Biomagnification: result of the processes of bioconcentration and bioaccumulation by which tissue concentrations of bioaccumulated chemicals increase as the chemical passes up through two or more trophic levels. The term implies an efficient transfer of chemical from food to consumer, so that residue concentrations increase systematically from one trophic level to the next.

Bornite: a copper iron sulphide mineral [Cu_5FeS_4].

Bryophyte: a plant of the phylum *Bryophyta*. A small groups of plants with wide distribution, and land and in water. Small, flat plants lacking vascular tissue.

Calcite: a calcium carbonate mineral [$CaCO_3$]. A very common and widely distributed mineral.

Carbonate Minerals: a group of minerals whose fundamental unit is the carbonate anion $(CO_3)^{-2}$. The common cations in carbonates are Ca^{+2}, Mg^{+2}, Fe^{+2}, Mn^{+2}, Zn^{+2}, Sr^{+2}, Ba^{+2}, Pb^{+2} and Cu^{+2}.

Carbonates: see "Carbonate Minerals". Also, sedimentary or metamorphic rocks composed primarily of carbonate minerals.

Cassiterite: a tin oxide mineral [SnO_2]. The most common ore of tin.

Chalcopyrite: a copper iron sulphide mineral [$CuFeS_2$]. A common and important ore of copper.

Chalcocite: a copper sulphide mineral [Cu_2S].

Chemical Oxygen Demand (COD): measure of the amount of oxygen required to oxidize organic and oxidizable inorganic compounds in water. The COD test is used to determine the degree of pollution in an effluent.

Chemocline: a zone of rapid change, with depth, in the concentration of dissolved substance in a lake. The boundary between the circulating and non-circulating layers of a lake.

Chronic: involving a stimulus that is lingering or continues for a long time; often signifies periods of several weeks to years, depending on the reproductive life cycle of the aquatic species. Can be used to define either the exposure or the response to an exposure (effect). Chronic exposure typically induces a biological response of relatively slow progress and long continuance. The chronic aquatic toxicity test is used to study the effects of continuous, long term exposure of a chemical or other potentially toxic material on aquatic organisms.

Cladoceran: any crustacean belonging to the order Cladocera, a group of about 400 species commonly known as water fleas, which includes *Daphnia magna*, frequently used in toxicity testing. Predominantly freshwater species, most cladocerans are 0.5 to 3 mm long. Most cladocerans are benthic, but some, such as *Daphnia* are planktonic. Morphologically, they are characterized by a univalve carapace that is bent along the back giving a bivalve appearance. This carapace encloses much of the body.

Clastic Rock: a sedimentary rock formed from mineral particles (clasts) that were mechanically transported.

Cobaltite: a cobalt sulpharsenide mineral [CoAsS].

Columbite-tantalite: a solid solution series of iron, manganese, niobium, tantalum oxide minerals [$(Fe,Mn)(Nb, Ta)_2O_6$]. These minerals are the most important ores of niobium and tantalum.

Community: in ecology, a collection of populations of animals and plants that occur naturally together in a common environment, such as the organisms inhabiting a lake. The individuals and populations within the community interact with one another and with the abiotic (non-living) surroundings, with the community and abiotic surroundings together constituting an ecosystem. Communities vary considerably in size and one large community may contain a number of smaller ones.

Compliance: in accordance with governmental permitting or regulatory requirements.

Conductivity: a numerical expression of the ability of an aqueous solution to carry an electric current. This ability depends on the concentrations of ion in solution, their valence and mobility, and on the solution's temperature. Conductivity in freshwater is normally reported in the SI unit of millisiemens per metre, or as micromhos per centimetre (1 mS/m = 10 μmhos/cm). Conductivity is a standard method for measuring salinity.

Contaminant: any physical, chemical or biological substance which is introduced into the environment. Does not imply and effect. Usually refers to substances of anthropogenic origin.

Crustaceans: invertebrates with exoskeleton, belonging to the Arthropod Phylum. There are more than 30,000 known species of crustaceans, ranging in size from planktonic species less than a millimetre in length to crabs with leg spans of 4 m. The class is usually aquatic, but is not restricted from the land. Examples include lobster, shrimp, crayfish, barnacles and water fleas.

Cubanite: a copper iron sulphide mineral [$CuFe_2S_3$].

Cumulative: brought about, or increased in strength, by successive additions at different times or in different ways.

Cyanide: a salt of hydrocyanic acid [HCN]. Occurs naturally in small concentrations. Used in aqueous solution in precious metal milling as a solvent to dissolved precious metals.

Daphnid: a freshwater microcrustacean, commonly known as a water flea. Species of daphnids include *Daphnia magna* and *D. pulex*.

Delayed Effects: effects or responses that occur some time after exposure.

Depuration: a process that results in elimination of a material from an organism.

Detection Limit: the smallest concentration or amount of a substance which can be reported as present with a specified degree of certainty by a definite, complete analytical procedure.

Diatom: a one-celled planktonic yellow-green algae that form siliceous cell walls. Occur in both freshwater and marine environments

Dimictic Lake: lake that circulates freely twice a year in the spring and fall and is directly stratified in summer, inversely stratified in winter. Dimictic lakes represent the most common type of thermal stratification observed in most lakes of the cool temperate regions of the world.

Dissolved Oxygen: the amount of oxygen present in solution in water, generally expressed in parts per million or mg/L.

Dolomite: a calcium magnesium carbonate mineral [$CaMg(CO_3)_2$].

DW: dry weight

EC_{50} (Median Effective Concentration): the concentration of material in water to which test organisms are exposed that is estimated to be effective in producing some sublethal response in 50% of the test organisms. Usually expressed as a time-dependent value (e.g., 24 hour or 96 hour EC_{50}).

Ecosystem: the physical and chemical environment of that community and all the interactions between organisms and between organisms and their environment. Also, a community of organisms occupying a given region within a biome.

Effluent: a complex waste material which is a by-product of human activity (i.e., liquid industrial discharge or sewage) which may be discharged to the environment.

Egg: an encapsulated, spherical ovum, unfertilized or fertilized, obtained from a sexually mature fish.

Eh: a measure of the oxidation reduction potential

Embryo: undeveloped young fish, before they hatch from eggs.

Enargite: a copper sulpharsenide mineral [Cu_3AsS_4].

Endpoint: the variable (e.g., time, reaction of the organisms, etc.) that indicates the termination of a test, and also means a measurement or value derived that characterizes the results of the test (NOEC, LC_{50}, etc.)

Epilimnion: the uppermost layer of water in a lake, characterized by an essentially uniform temperature that is generally warmer than elsewhere in the lake and by a relatively uniform mixing caused by wind and wave action. Also the light (less dense) oxygen-rich layer of water that overlies the metalimnion in a thermally stratified lake.

Erythrite: an hydrated cobalt arsenate mineral [$Co_3(AsO_4)_2 \cdot 8H_2O$], formed through the oxidation of cobalt arsenide and sulpharsenide minerals.

Eutrophic Waters: waters with abundant nutrients and having high rates of productivity resulting in oxygen depletion below the surface layer in the water body.

Eyed Egg: is an encapsulated fish embryo that has reached a stage of development where its eyes are clearly evident to the casual observer.

Fate: disposition of a material in various environmental compartments (e.g., sediment, water, tissue) as a result of transport, transformation and degradation.

Felsic: a generally light coloured silicate mineral, containing no metals (quartz), or containing primarily K, Al, Na and Ca. Also, a light coloured igneous rock composed predominantly of felsic minerals.

Fingerling: a young (underyearling), actively feeding fish.

Food Chain: a specific nutrient and energy pathway in ecosystems proceeding from producer to consumer.

FW: fresh weight

Galena: a lead sulphide mineral [PbS]. An important ore of lead.

Glacial Till: a heterogenous mixture of angular fragments of rock, sand, and clay, deposited on the ground as glaciers retreat. Layers of till can range in thickness from less than 1 m to hundreds of metres.

Goethite: an iron oxyhydroxide mineral [FeO(OH)]. Forms through the oxidation of iron minerals.

Gypsum: an hydrated calcium sulphate mineral [$CaSO_4 \cdot 2H_2O$].

Habitat: a geographic area that can provide for the key activities of life.

Hardness: the sum of calcium and magnesium concentrations, both expressed as $CaCO_3$, in milligrams per litre. Other ions such as iron, manganese and aluminum contribute to total hardness, although they are usually present in much smaller concentrations and thus do not normally make a significant contribution to the total hardness. Waters if various hardness are classified as follows:

Hardness = 1 to 60 mg/L as $CaCO_3$ → soft water
Hardness = 61 to 120 mg/L as $CaCO_3$ → medium to hard water
Hardness = 121 to 180 mg/L as $CaCO_3$ → hard water
Hardness > 181 mg/L as $CaCO_3$ → very hard water

Heavy Metal: metallic elements with relatively high atomic weights (> 5.0 specific gravity) such as lead, cadmium, arsenic and mercury. Generally toxic in relatively low concentrations to plant and animal life.

Holomictic Lake: a lake in which circulation occurs throughout the entire water column.

Hydroxide Minerals: a group of minerals whose fundamental unit is the hydroxide anion, OH-. The common cations in hydroxides are Mg^{+2}, Al^{+3}, Fe^{+2}, and Mn^{+2}.

Hydroxides: see "Hydroxide Minerals"

Hypolimnion: the lowermost layer of water in a lake, characterized by an essentially uniform temperature (except during a turnover) that is generally colder than elsewhere in the lake, and often by relatively stagnant or oxygen-poor water. Also the dense layer of water below the metalimnion in a thermally stratified lake.

Igneous Rock: One of three main groups of rocks. Rocks formed as a result of the solidification of molten rock (magma). Igneous rocks may be either extrusive on the earth's surface (volcanic), or intrusive into the earth's crust (plutonic). Extrusive igneous rocks are fine grained (crystals < 1 mm), and intrusive igneous rocks are medium to coarse grained (crystals 1 mm to > 3 cm). Most igneous rocks are composed primarily of silicate minerals, and can be either felsic or mafic in mineralogical composition.

Inorganic: matter other than plant or animal, and not containing a combination of carbon/hydrogen/oxygen as in living things.

Invertebrate: an animal without an internal skeletal structure. Invertebrates may have exoskeletons (e.g. lobster) or no skeletal structure (e.g. jellyfish).

Isopod: any crustacean belonging to the order Isopoda. The isopods include over 4,000 marine, freshwater and terrestrial species, and range in length from 0.5 to 440 mm. Most are herbivorous or omnivorous scavengers.

Larva: a recently hatched fish which has physical characteristics other than those seen in adult fish. The larval period begins with the hatching of the embryo and lasts until the disappearance of the last vestige of the median fin fold and the appearance of a full complement of fin rays.

LC_{50}: the median lethal concentration, i.e., the concentration of material in water that is estimated to be lethal to 50% of the test organisms. The LC_{50} and its 95% confidence limits are usually derived by statistical analysis of mortalities in several test concentrations after a fixed period of exposure. The duration of exposure must be specified (e.g. 96 hour LC_{50}).

Leachate: liquids that have percolated through a soil and that contain substances in solution or suspension.

Lethal: Causing death by direct action. Death of fish is defined as the cessation of all visible signs of movement or other activity.

Limestone: a sedimentary rock consisting essentially of carbonate minerals, particularly calcite or dolomite. May be formed as a result of: accumulation and lithification of shells of marine organisms; chemical precipitation of carbonate minerals; or the mechanical accumulation of fragments of carbonate minerals.

LOEC (lowest observed effect concentration): the lowest concentration of a test material in which the response observed is verified by statistical testing to be different than the control response (see NOEC). For example, if growth is the most sensitive end point, the LOEC might be the lowest concentration at which growth of fish differed significantly from that in the control. LOEC is generally reserved for sublethal effects but can also be used for mortality, which may sometimes be the most sensitive effect observed.

Mafic: a dark coloured silicate mineral rich in Fe and Mg. Also, a dark coloured igneous rock composed predominantly of mafic minerals.

Marcasite: an iron sulphide mineral [FeS_2].

Meromictic Lake: a lake that at the time of winter cooling undergoes only a partial circulation down to a depth determined by a density stratification.

Metalimnion: see "Thermocline"

Metamorphic Rock: One of thee main groups of rocks. Rock formed as a result of high pressure and/or temperature changing the properties or characteristics of pre-existing rock. The pre-existing rock can be of any rock type. Changes may include recrystallization of the minerals in the rock, a realignment of mineral grains in the rock, or a change in the chemical composition of the rock as a result of reaction with high temperature fluids. Metamorphic rocks are formed deep in the earth's crust.

Metamorphic Grade: a measure of the intensity of metamorphism which a rock has undergone. Low grade metamorphic rocks have been exposed to less intense pressure and/or temperature than high grade metamorphic rocks. Grade is defined by the "metamorphic facies" which is marked by characteristic changes in mineralogy. The most common metamorphic facies in Canada are, from lowest to highest grade: greenschist facies, amphibolite facies, and granulite facies.

Millerite: a nickel sulphide mineral [NiS].

Molybdenite: a molybdenum sulphide mineral [MoS_2]. A important ore of molybdenum.

NOEC (no observed effect concentration): the highest concentration of a test material to which organisms are exposed, in which the response is found, by some statistical test, not to be different from the control response (see LOEC) (e.g., value of an observed variable such as growth does not differ significantly from that in the control). NOEC customarily refers to sublethal effects and to the most sensitive effect unless otherwise specified.

Nutrient: a substance, element or compound necessary for the growth and development of plants and animals.

Oligotrophic Waters: waters with a deficiency of nutrients and plentiful amounts of dissolved oxygen. They support little organic production.

Ore: a natural deposit in which a metallic mineral occurs in sufficient concentrations to make mining the mineral economically feasible.

Ore Reserves: an estimate of the amount of recoverable ore present.

Ore Grade: the proportion of recoverable metal within an ore body.

Organic Compounds: chemical compounds based on carbon chains or rings, and also containing hydrogen with or without oxygen, nitrogen or other elements.

Organics: see "Organic Compounds".

Orpiment: an arsenic sulphide mineral [As_2S_3]. Uncommon in Canada.

Oxidation: a chemical reaction in which electrons are lost from an atom and its charge becomes more positive. Normally, oxidation involves the addition of atmospheric oxygen or water. Oxidation occurs concurrently with reduction.

Oxide Minerals: a group of minerals whose fundamental unit is oxygen, O^{-2}. The common cations in oxides include: Cu^{+2}, Mg^{+2}, Al^{+3}, Fe^{+2}, Mn^{+2}, Ti^{+2}, Cr^{+2} and Sn^{+2}.

Oxides: see "Oxide Minerals".

Parts Per Billion (ppb): one unit of chemical (usually expressed as mass) per 1,000,000,000 units of the medium (e.g., water) or organism (e.g., tissue) in which it is contained. For water, the ratio commonly used is micrograms of chemical per litre of water, 1 μg/L = 1 ppb, for tissues, 1 μg/kg = 1 ng/g = 1 ppb.

Parts Per Million (ppm): one unit of chemical (usually expressed as mass) per 1,000,000 units of the medium (e.g., water) or organism (e.g., tissue) in which it is contained. For water, the ratio commonly used is milligrams of chemical per litre of water, 1 mg/L = 1 ppm, for tissues, 1 mg/kg = 1 μg/g = 1 ppm.

Pentlandite: an iron nickel sulphide mineral [$(Fe,Ni)_9S_8$]. An important ore of nickel.

Periphyton: the association of aquatic organisms attached or clinging to stems and leaves of rooted plants or other surfaces projecting above the bottom of a water body.

pH: a measure of the acidity or alkalinity of water, sediment or soil. The measure is based on the concentration of hydrogen ions, and gives the negative logarithm of the hydrogen (H^+) ion, corresponding to 10^{-7}. A pH value of 7 is neutral. All values higher are considered alkaline, and all values lower are considered acidic.

Phytoplankton: plants that live in the water column and float and drift in the water and are dependent on currents and other water movements. See also "Plankton".

Plankton: plants and animals which live in the water column, but which float and drift in the water and are dependent on currents and other water movements. Most planktonic animals have means of locomotion, but because of their small size they are carried by currents. Planktonic animals may spend all or of their lives as plankton, depending on the species.

Platinum Group Metals: a group of six precious metals: platinum (Pt), palladium (Pd), iridium (Ir), rhodium (Rh), osmium (Os), and ruthenium (Ru).

Platinum Group Minerals: a group of sulphide minerals which contain platinum group metals.

Population: a group of organisms of the same species living within a specified region. Populations have certain characteristics not shown by individual organisms or the community as a whole. Characteristics of a populations include density (size in relation to unit space), birth and death rates, age distribution, sex ratio, dispersion (distribution of individuals within the region) and growth rate.

Pyrite: an iron sulphide mineral [FeS_2]. The most common and most widespread sulphide mineral. Occurs in a wide range of ore deposit types. Occasionally mined as a source of sulphur, but not as a source of iron. Also known as "fool's gold"

Pyrochlore-microlite: a solid solution series of niobium tantalum oxide minerals with the formulae: $(Na,Ca)_2Nb_2O_6(OH,F) \rightarrow (Na,Ca)_2Ta_2O_6(O,OH,F)$.

Pyrolusite: a manganese oxide mineral [MnO_2]. Forms through the oxidation of manganese bearing minerals.

Pyrrhotite: an iron sulphide mineral with a variable sulphur content, giving the formula $Fe_{1-x}S$.

Quartz: a silicate mineral [SiO_2]. One of the most common minerals in the world, occurring in a very wide range of rock types.

Realgar: an arsenic sulphide mineral [AsS]. Uncommon in Canada.

Reduction: a chemical reaction in which electrons are gained by an atom and its charge becomes more negative. Reduction occurs concurrently with oxidation.

Rotifer: any invertebrate animal belonging to the phylum Rotifera, a group of about 1,800 species which range in size from less than 1 mm to 3 mm in length. Most species occur in freshwater, but marine and a few terrestrial species also occur. Aquatic species may be benthic or planktonic.

Safflorite: a cobalt iron nickel arsenide mineral [$(Co,Fe,Ni)As_2)$].

Salinity: the total amount of solid material, in grams, dissolved in 1 kg of solution.

Salmonid: a fish of the family *Salmoniidae*. Fish in this family include salmon and trout.

Sandstone: a sedimentary rock consisting essentially of silicate minerals, particularly quartz and/or feldspar. Consists of grains ranging in size from 1/16 mm to 2 mm, cemented together by either silicate or carbonate minerals. May be formed as a result of accumulation of grains due to either wind or water action.

Scheelite: a calcium tungstate mineral [$CaWO_4$]

Scorodite: an hydrated iron arsenate mineral [$FeAsO_4 \cdot 2H_2O$], formed through the oxidation of iron arsenide and sulpharsenide minerals.

Sediment: solid fragmental material that originates from weathering or rocks and is transported or deposited by air, water or ice, or that accumulated by other processes, such as chemical precipitation from solution or secretion by organisms. The term is usually applied to material held in suspension in water or recently deposited from suspension and to all kinds of deposits, essentially of unconsolidated materials.

Selenide Mineral: a metallic mineral characterized by the covalent bonding of selenium with a metal such as iron, copper, lead, zinc, nickel or molybdenum. An example of a selenide mineral is eucairite, which has the chemical formula CuAgSe.

Selenides: see "Selenide Mineral"

Shale: a very fine grained detrital sedimentary rock composed of silt and clay which tends to part along bedding planes.

Shellfish: an aquatic invertebrate, such as a mollusc or crustacean, that has a shell or exoskeleton.

Siderite: an iron carbonate mineral [$FeCO_3$].

Silicate Mineral: a large group of minerals whose fundamental unit is SiO_4. A wide range of metals can occur in silicates, including Fe, Mg, K, Al, and Ca. Silicates comprise about one third of all mineral species, and are important rock forming minerals, comprising up to 95% of the earth's crust.

Silicates: see "Silicate Mineral".

Skutterudite: a cobalt nickel arsenide mineral [$(Co,Ni)As_{2-3}$].

Slurry: a fluid mixture of liquids and solids.

Species: a group of plants, animals or microorganisms that have a high degree of similarity and generally can generally interbreed only among themselves.

Sphalerite: a zinc iron sulphide mineral [$(Zn,Fe)S$]. The most important zinc ore mineral. Cadmium commonly substitutes for Zn.

Standing Crop: the weight of organic material that can be sampled or harvested by normal methods at any one time from a given area.

Sublethal: detrimental to the organism, but below the level that directly causes death within the test period.

Sulpharsenide Mineral: a metallic mineral characterized by the covalent bonding of sulphur and arsenic with a metal such as iron, copper, lead, zinc, nickel or molybdenum. An example of a common sulpharsenide mineral is arsenopyrite, which has the chemical formula FeAsS.

Sulpharsenides: see "Sulpharsenide Mineral"

Sulphate Mineral: a mineral characterized by the bonding of sulphate anion with a metal such as barium, calcium, lead or copper. Sulphates may or may not include water in their structure. Common examples include barite [$BaSO_4$] and gypsum [$CaSO_4 \cdot 2H_2O$].

Sulphate: an anion with the formula SO_4^{-2}.

Sulphates: see "Sulphate Mineral"

Sulphide Mineral: a metallic mineral characterized by the covalent bonding of sulphur with a metal or semimetal, such as iron, copper, lead, zinc, nickel or molybdenum. An example of a common sulphide mineral is pyrite, which has the chemical formula FeS_2. Sulphide minerals occur in a wide range of geological environments. When occurring in sufficient concentrations, sulphide minerals can be important ore minerals for a range of base metals, including copper, lead, zinc and nickel.

Sulphides: see "Sulphide Mineral"

Sulphosalt Mineral: a type of sulphide mineral in which both a metal and a semimetal occur. For example, enargite, Cu_3AsS_4, would be considered a sulphosalt since it contains both arsenic and sulphur. Such minerals may also be considered sulpharsenides.

Sulphosalts: see "Sulphosalt Mineral"

Suspended Solids: and solid substance present in water in an undissolved state, usually contributing directly to turbidity.

Swim-up Fry: a young, post-alevin fish which has commenced active feeding.

Tailings: second grade or waste mineral fragments derived from screening or processing of raw ores.

Thermocline: the layer in a thermally stratified lake, between the epilimnion and hypolimnion, in which the temperature decreases most rapidly with depth. The horizontal layer of water characterized by a rapid decrease in temperature and increase of density with depth; sometimes arbitrarily defined as the layer in which the rate of temperature decrease with depth is equal to at least 1°C per metre. Also known as "metalimnion".

Total Dissolved Solids (TDS): the concentration of dissolved substances in a water, usually expressed in milligrams per litre.

Toxicity: the inherent potential or capacity of a material to act on a group of selected organisms, under defined conditions. An aquatic toxicity test usually measures the proportion of organisms affected by their exposure to specific concentrations of chemical, effluent, elutriate, leachate, or receiving water.

Toxicity Test: the means by which the toxicity of a chemical or other test material is determined. A toxicity test is used to measure the degree of response produced by exposure to a specific level of stimulus (or concentration of chemical).

Turbidity: the extent to which the clarity of water has been reduced by the presence of suspended, colloidal organic or inorganic or other matter that causes light to be scattered and absorbed rather than transmitted in straight lines, resulting in the water appearing cloudy to opaque.

Ultramafic: a rock with a composition completely dominated by mafic minerals. Ultramafic rocks contain no quartz, and less than 10% other felsic minerals. Chromium and platinum group metal deposits are hosted exclusively by ultramafic rocks.

Uraninite: a uranium oxide mineral [UO_2]. An important ore of uranium.

Volcanic Rock: a fine grained mafic or felsic igneous rock formed as a result of molten rock being extruded on the surface of the earth, either on land, or on the sea floor.

Volcanics: see "Volcanic Rock"

Volcanogenic: formed as a result of volcanic activity. Volcanogenic massive sulphide deposits form as a result of volcanic activity on the sea floor.

Wetlands: habitats where the influence of surface or ground water has resulted in the development of plant or animal communities adapted to such aquatic or intermittently wet conditions. Wetlands include tidal flats, shallow subtidal areas, swamps, marshes, wet meadows, bogs, muskeg, and similar areas.

Wolframite: an iron manganese tungstate mineral [$(Fe,Mn)WO_4$]. An important ore of tungsten.

Xenobiotic: a foreign chemical or material not produced in nature and not normally considered a constitutive component of a specified biological system. This term is usually applied to manufactured chemicals.

Zooplankton: animals which live in the water column, but which float and drift in the water and are dependent on currents and other water movements. See also "Plankton".

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Appendix 1: Flowsheets for Mineral Separation Processes

(all flowsheets after Environmental Applications Group, 1992)

Figure A.1.1: Typical Base Metal Flowsheet (Copper, Lead, Zinc)

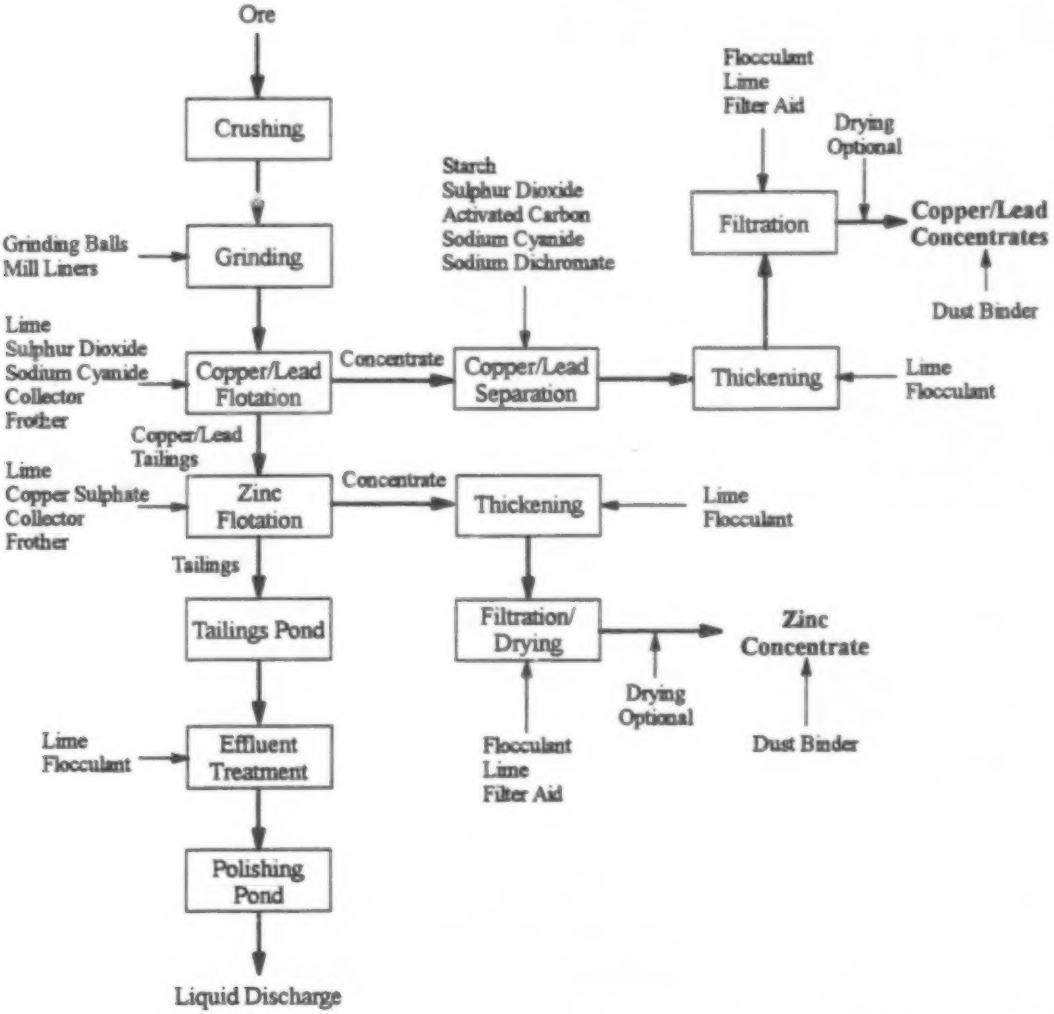

Ore
Crushing
Grinding Balls
Mill Liners
Grinding
Lime
Sulphur Dioxide
Sodium Cyanide
Collector
Frother
Copper/Lead Flotation
Concentrate
Starch
Sulphur Dioxide
Activated Carbon
Sodium Cyanide
Sodium Dichromate
Copper/Lead Separation
Thickening
Lime
Flocculant
Flocculant
Lime
Filter Aid
Filtration
Drying Optional
Copper/Lead Concentrates
Dust Binder
Copper/Lead Tailings
Lime
Copper Sulphate
Collector
Frother
Zinc Flotation
Concentrate
Thickening
Lime
Flocculant
Tailings
Tailings Pond
Filtration/ Drying
Zinc Concentrate
Drying Optional
Dust Binder
Flocculant
Lime
Filter Aid
Lime
Flocculant
Effluent Treatment
Polishing Pond
Liquid Discharge

Figure A.1.2: Typical Base Metal Flowsheet (Nickel, Copper)

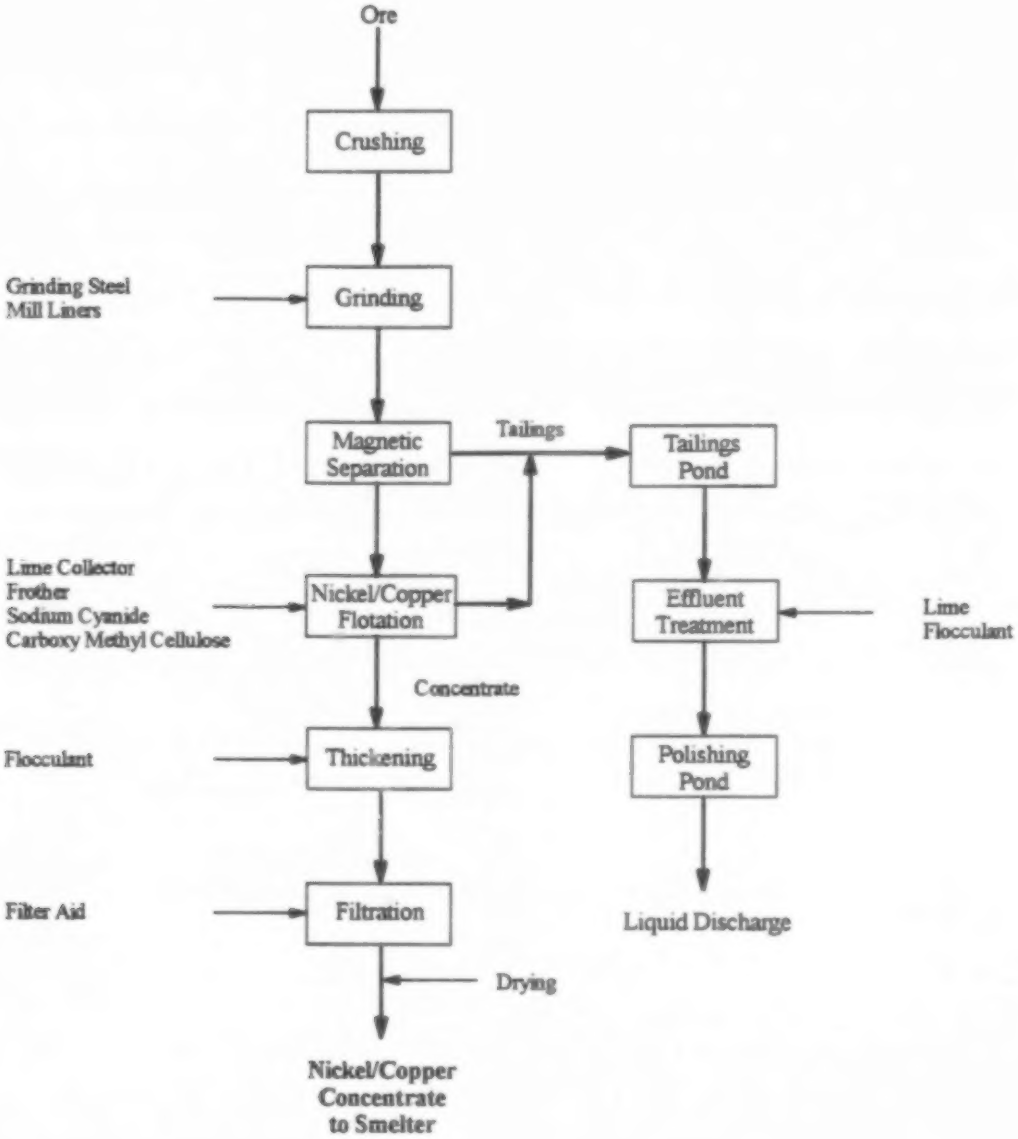

Ore
Crushing
Grinding Steel
Mill Liners
Grinding
Magnetic Separation
Tailings
Tailings Pond
Lime Collector
Frother
Sodium Cyanide
Carboxy Methyl Cellulose
Nickel/Copper Flotation
Effluent Treatment
Lime
Flocculant
Concentrate
Flocculant
Thickening
Polishing Pond
Filter Aid
Filtration
Liquid Discharge
Drying
Nickel/Copper Concentrate to Smelter

Figure A.1.3: Typical Iron Ore Flowsheet (Wet Process)

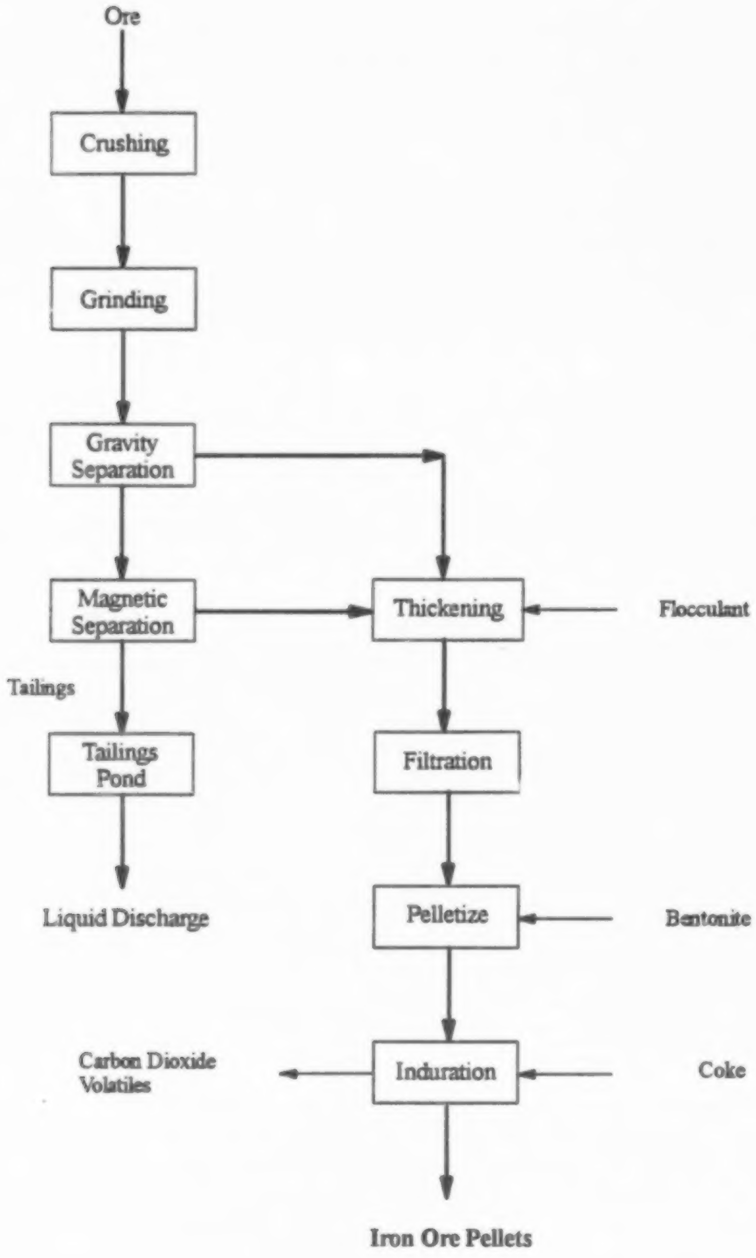

Ore
Crushing
Grinding
Gravity Separation
Magnetic Separation
Thickening
Flocculant
Tailings
Tailings Pond
Filtration
Liquid Discharge
Pelletize
Bentonite
Carbon Dioxide
Volatiles
Induration
Coke
Iron Ore Pellets

Figure A.1.4: Typical Uranium Flowsheet (Saskatchewan)

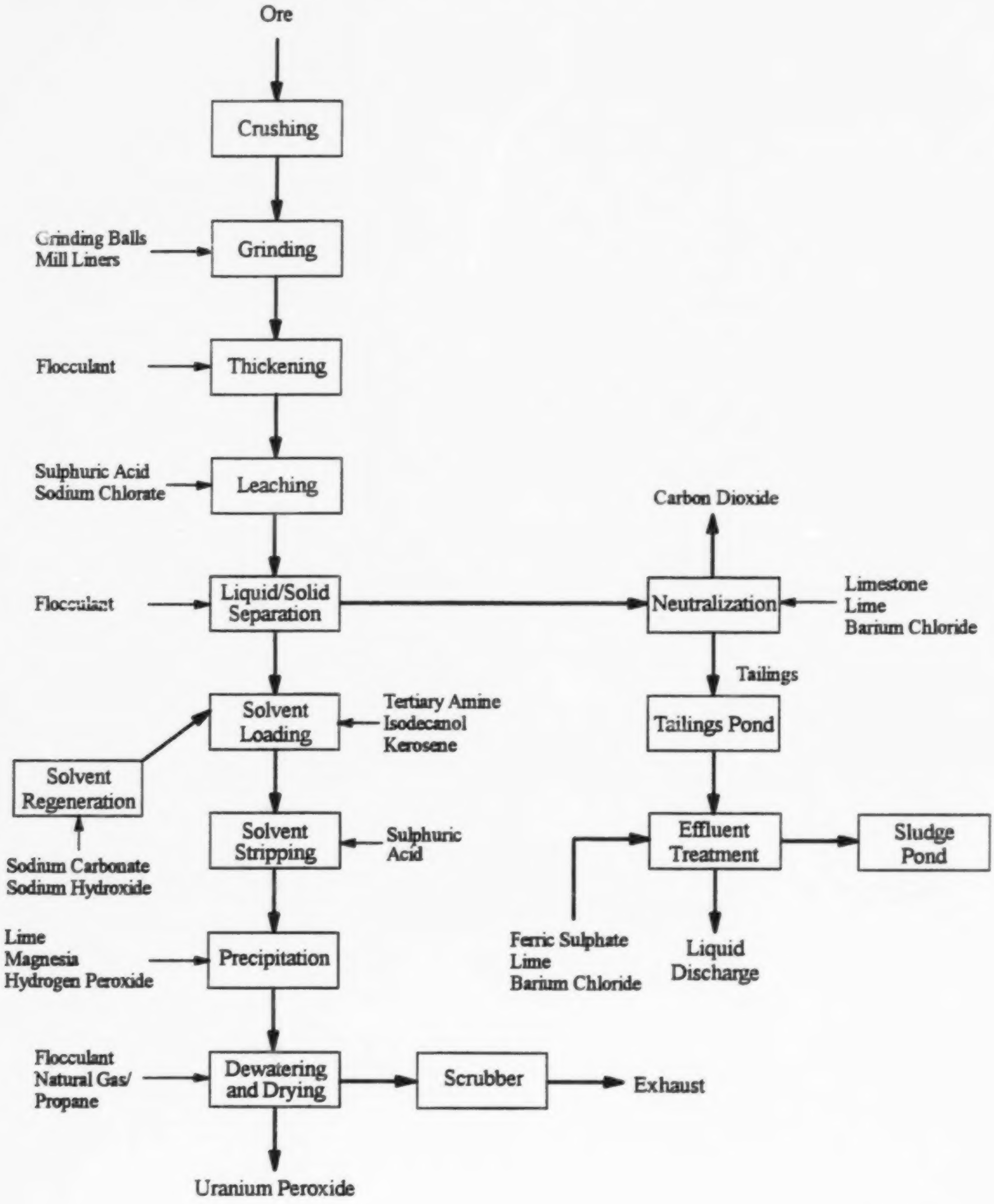

Ore
Crushing
Grinding Balls
Mill Liners
Grinding
Flocculant
Thickening
Sulphuric Acid
Sodium Chlorate
Leaching
Carbon Dioxide
Flocculant
Liquid/Solid Separation
Neutralization
Limestone
Lime
Barium Chloride
Tailings
Solvent Loading
Tertiary Amine
Isodecanol
Kerosene
Tailings Pond
Solvent Regeneration
Sodium Carbonate
Sodium Hydroxide
Solvent Stripping
Sulphuric Acid
Effluent Treatment
Sludge Pond
Ferric Sulphate
Lime
Barium Chloride
Liquid Discharge
Lime
Magnesia
Hydrogen Peroxide
Precipitation
Flocculant
Natural Gas/
Propane
Dewatering and Drying
Scrubber
Exhaust
Uranium Peroxide

Figure A.1.5: Typical Gold Flowsheet (Merrill Crowe)

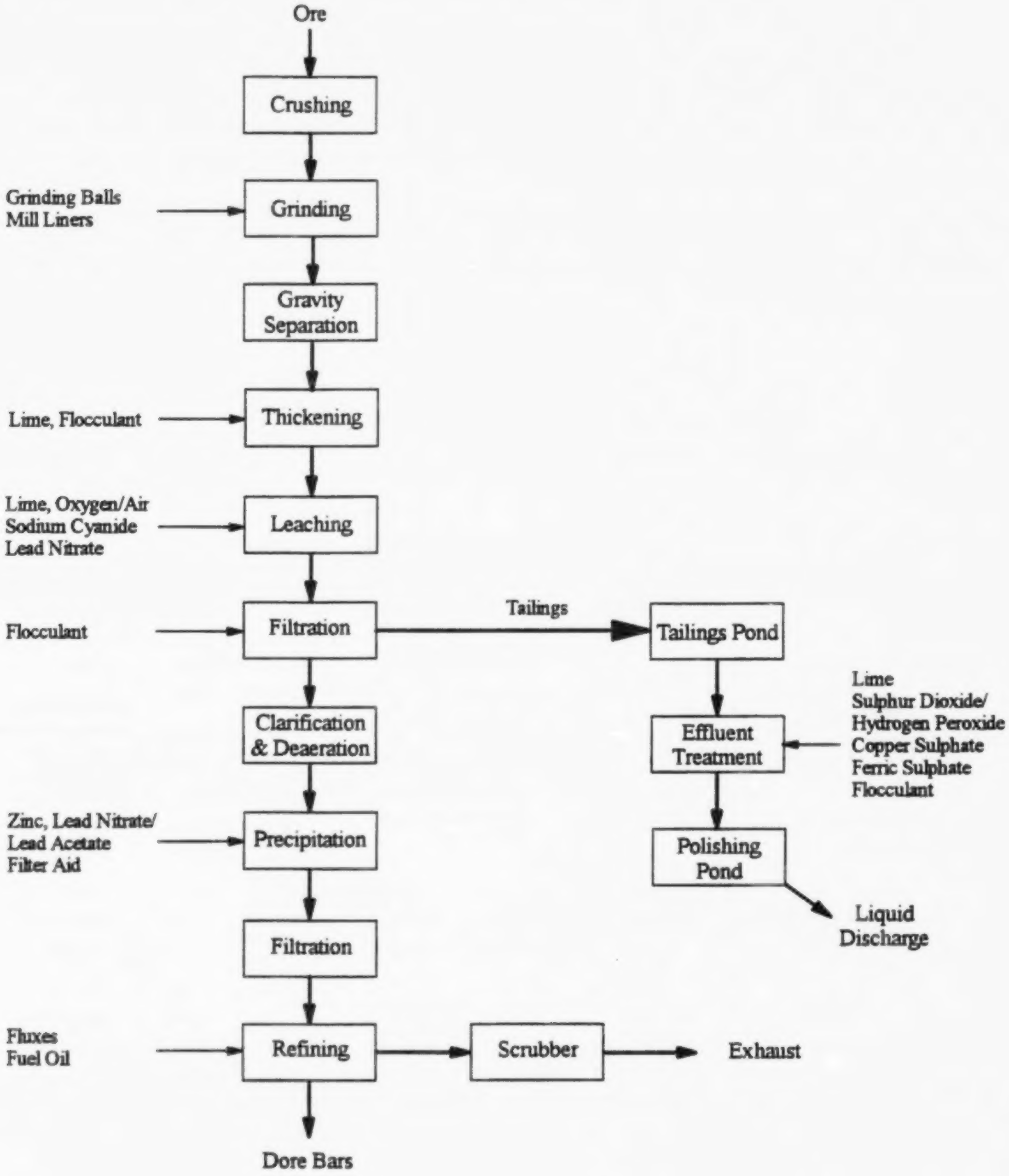
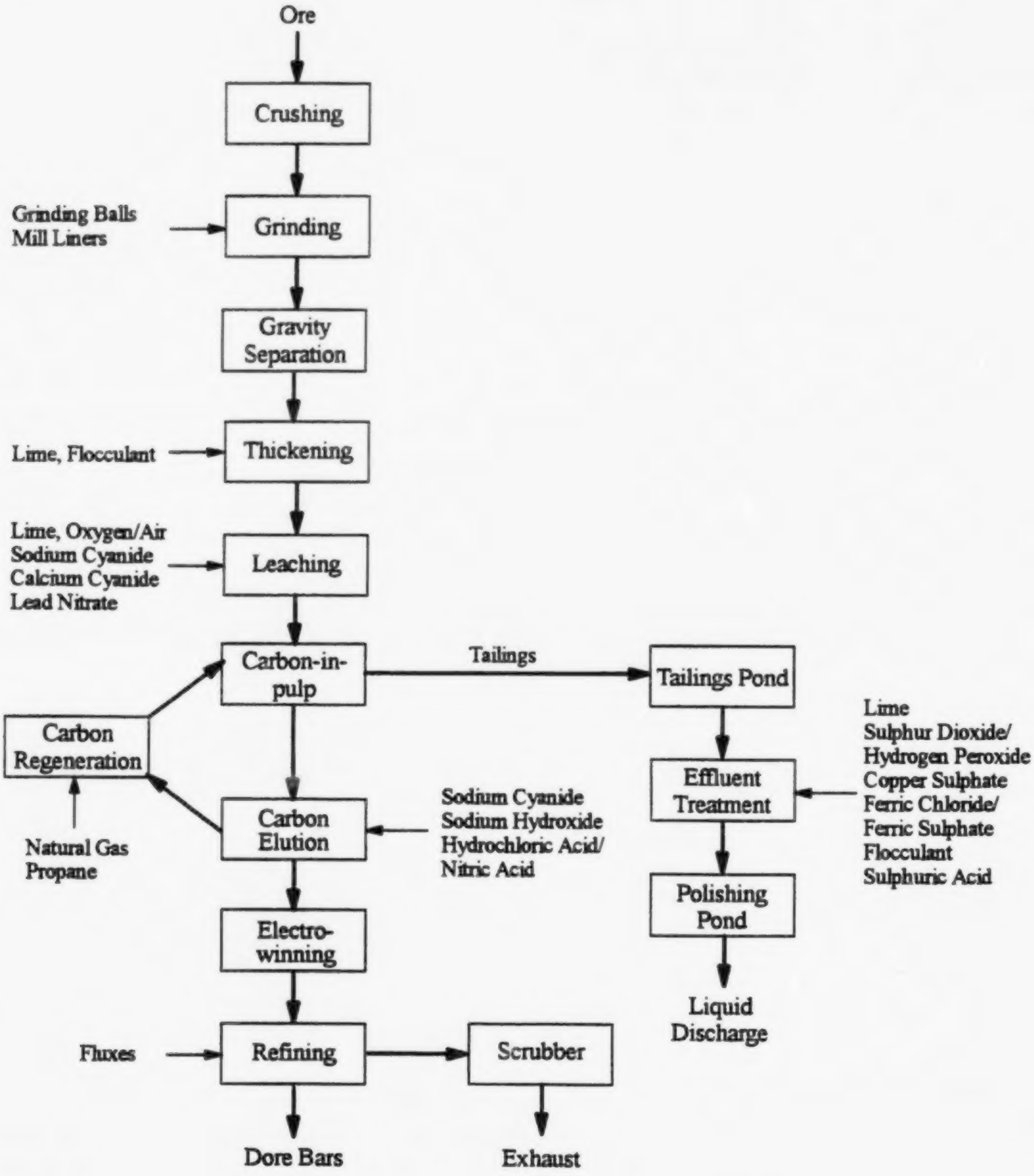

Ore
Crushing
Grinding Balls
Mill Liners
Grinding
Gravity Separation
Lime, Flocculant
Thickening
Lime, Oxygen/Air
Sodium Cyanide
Lead Nitrate
Leaching
Flocculant
Filtration
Tailings
Tailings Pond
Lime
Sulphur Dioxide/
Hydrogen Peroxide
Copper Sulphate
Ferric Sulphate
Flocculant
Effluent Treatment
Polishing Pond
Liquid Discharge
Clarification & Deaeration
Zinc, Lead Nitrate/
Lead Acetate
Filter Aid
Precipitation
Filtration
Fluxes
Fuel Oil
Refining
Scrubber
Exhaust
Dore Bars

Figure A.1.6: Typical Gold Flowsheet (Carbon-in-Pulp)


Ore
Crushing
Grinding Balls
Mill Liners
Grinding
Gravity Separation
Lime, Flocculant
Thickening
Lime, Oxygen/Air
Sodium Cyanide
Calcium Cyanide
Lead Nitrate
Leaching
Carbon-in-pulp
Tailings
Tailings Pond
Carbon Regeneration
Natural Gas
Propane
Carbon Elution
Sodium Cyanide
Sodium Hydroxide
Hydrochloric Acid/
Nitric Acid
Effluent Treatment
Lime
Sulphur Dioxide/
Hydrogen Peroxide
Copper Sulphate
Ferric Chloride/
Ferric Sulphate
Flocculant
Sulphuric Acid
Polishing Pond
Liquid Discharge
Electro-winning
Fluxes
Refining
Scrubber
Dore Bars
Exhaust

Appendix 2: Reagent Consumption at Canadian Metal Mines

Table A.2.1: Reagent consumption in 1993 at selected Canadian base metal mine/mill sites, in pounds per ton of ore milled, and thousands of pounds per day.

Site	STPD Ore Milled	Frother	Collector	Lime	Cyanide	pH Modifier	Activator	Flocculant/ Coagulant
Highland Valley	154,000	0.05 / 8	0.12 / 18.5	1.40 / 215				
Myra Falls	4,400	0.04 / 0.2	0.31 / 1.4	3.00 / 13.2			1.18 / 5.2	0.02 / 0.09
Bell Copper	18,700	0.03 / 0.5	0.01 / 0.17	1.92 / 35.9				0.001 / 0.02
Brenda	36,300	0.06 / 2.3	0.22 / 7.9		0.01 / 0.29			0.002 / 0.07
Endako	33,000	0.07 / 2.2	0.15 / 4.9		0.02 / 0.6			0.02 / 0.5
Island Copper	60,500	0.07 / 4.4	0.01 / 0.5	1.10 / 66	0.51 / 31			0.10 / 6.3
Faro	14,300	0.05 / 0.6	0.30 / 4.3	2.60 / 37	0.20 / 2.8		1.01 / 14.5	0.002 / 0.03
Nanisivik	2,200	0.01 / 0.02	0.32 / 0.7	4.80 / 10.6			1.24 / 2.7	
Flin Flon	8,470	0.03 / 0.2	0.12 / 1	3.75 / 31.2	0.001 / 0.01		0.07 / 0.6	0.10 / 0.8
Thompson	19,800	0.08 / 1.6	0.10 / 2	0.80 / 15.8		3.20 / 63.4		
Clarabelle	30,030	0.04 / 1.2	0.11 / 3.3	3.00 / 90	0.10 / 3			0.01 / 0.3
Strathcona	9,020	0.19 / 1.7	0.16 / 1.5	1.86 / 16.8	0.02 / 0.2		0.05 / 0.5	0.006 / 0.05
Geco	4,070	0.027 / 0.1	0.06 / 0.2	1.22 / 5	0.11 / 0.5		0.58 / 2.3	0.001 / 0.004
Kidd Creek	14,300	0.03 / 0.5	0.17 / 2.4	1.19 / 17	0.03 / 0.4		0.87 / 12.5	
Winston Lake	1,100	0.70 / 0.8	0.05 / 0.06	2.60 / 2.9			2.26 / 2.5	0.004 / 0.004
Isle Dieu	605	0.028 / 0.02	0.16 / 0.1	5.00 / 3		0.84 / 0.5	0.01 / 0.005	
Niobec	3,850	0.01 / 0.04	1.24 / 4.8					0.02 0.08
Selbaie	3,190	0.05 / 0.2	0.09 / 0.3	4.14 / 13.2	0.01 / 0.03		0.53 / 1.7	0.07 / 0.2
Gaspe	5,500	0.06 / 0.3	0.06 / 0.3					0.004 / 0.02
Horne	1,210	0.12 / 0.15	0.49 / 0.15					
Lac Matagami	3,300	0.04 / 0.14	0.19 / 0.6	3.88 / 12.8			0.87 / 2.9	0.01 / 0.3
Norbec	1,265	0.04 / 0.05	0.16 / 0.2	2.06 / 2.6				0.002 / 0.002
Brunswick	11,000	0.002 / 0.02	0.44 / 4.8	11.8 / 129.8		5.40 / 59.4	1.40 / 15.4	0.01 / 0.1
Heath Steele	3,960		0.17 / 0.66	2.40 / 9.5	0.04 / 0.16		1.74 / 6.9	
Rio Kemptville	9,900	0.004 / 0.04	0.009 / 0.09	1.14 / 11.3	0.003 / 0.03	0.05 / 0.5	0.009 / 0.09	0.001/0.01
Gays River	1,485	0.002 / 0.003	0.44 / 0.65	11.80 / 17.5		5.40 / 8.0	1.40 / 2.0	0.01 / 0.01

Table A.2.2: Reagent consumption in 1993 at Canadian iron and uranium mine/mill sites, in pounds per ton of ore milled, and thousands of pounds per day

Mill	STPD Ore Milled	Frother	Collector	Lime	Cyanide	pH Modifier	Activator	Flocculant/ Coagulant
Iron Ore								
Algoma	9,900							0.05 / 0.5
Lac Tio	8,250							0.05 / 0.4
Mont Wright	55,000							0.05 / 2.7
Iron Ore of Canada	154,000							0.05 / 7.7
Scully	59,840							0.05 / 3
Uranium								
Cluff Lake	1,100			32.2 / 35.4		64.4 / 70.8		0.48 / 0.5
Rabbit Lake	1,815			39.9 / 72.5		29.7 / 54		0.32 / 0.6
Key Lake	1,020		0.34 / 0.35	150 / 153		248 / 253		0.92 / 0.94
Denison	15,015	7.00 / 105	2.50 / 37.5	22.0 / 330		139 / 2087		0.88 / 13.2
Quirke*	7,040			23.0 / 161.9		110 / 774		0.18 / 1.3
Panel*	3,300			23.8 / 78.5		97.5 / 321.7		0.064 / 0.2
Stanleigh	4,950			35.0 / 173		70.0 / 346		0.08 / 0.4

* 1990 data

Table A.2.3: Reagent consumption in 1993 at selected Canadian gold mine/mill sites using cyanide, in pounds per ton of ore milled, and thousands of pounds per day

Gold Mills with Cyanidation	STPD Ore Milled	Frother	Collector	Lime	Cyanide	pH Modifier	Activator	Flocculant/ Coagulant
Equity	9,460	0.4 / 3.7	0.19 / 1.8	2.06 / 19.5	2.01 / 19.0	1.14 / 10.8	0.25 / 2.2	0.01 / 0.1
Lawyers	570	0.10 / 0.06	0.12 / 0.07	3.00 / 1.7	1.50 / 0.8		0.04 / 0.02	0.10 / 0.06
Nickel Plate	3,630			5.50 / 20.0	2.50 / 9.0	0.04 / 0.15	0.14 / 0.51	0.16 / 0.58
Premier	2,530			1.98 / 5.0	0.97 / 2.5	0.85 / 2.2	0.08 / 0.2	0.14 / 0.35
Con	935	0.03 / 0.03	0.20 / 0.19	1.20 / 1.1	1.10 / 1.0		0.50 / 0.47	
Giant	1,375	0.16 / 0.21	0.34 / 0.47	3.27 / 4.5	0.79 / 1.1	0.05 / 0.07	0.13 / 0.18	0.02 / 0.03
Lupin	2,295			1.45 / 3.3	1.29 / 3.0		0.67 / 1.5	0.01 / 0.03
Joutel	1,980	0.06 / 0.12	0.53 / 1.0	6.51 / 12.9	0.57 / 1.1	0.30 / 0.59	0.43 / 0.85	0.01 / 0.02
East Malartic	2,750	0.02 / 0.05	0.08 / 0.21	13.70 / 37.7	6.60 / 18.1			0.01 / 0.04
Campbell	1,570	0.01 / 0.02	0.38 / 0.60	2.54 / 4.0	2.32 / 3.6	0.09 / 0.14	0.26 / 0.41	0.01 / 0.02
Detour	2,420			1.5 / 3.6	1.60 / 3.9		0.90 / 2.2	
Dome	4,620			1.64 / 7.6	0.40 / 1.9	0.05 / 0.24		0.01 / 0.05
David Bell	1,430			1.00 / 1.4	0.54 / 0.77			
Golden Giant	3,300			0.10 / 0.33	1.10 / 3.6	0.24 / 0.79		
Holt-McDermott	1,500			4.16 / 6.2	0.84 / 1.3	0.42 / 0.63		0.01 / 0.01
Kerr	2,420			2.00 / 4.8	1.50 / 3.6			
Macassa	1,375			14.00 / 19.2	1.40 / 1.9		1.90 / 2.6	0.20 / 0.27
Pamour No. 1	3,740	0.12 / 0.45	1.01 / 3.8	7.40 / 27.7	0.64 / 2.4		0.04 / 0.15	
Bousquet No. 1*	1,925			4.61 / 8.9	1.97 / 3.8		0.06 / 0.12	0.01 / 0.03
Bousquet No. 2*	1,650			9.00 / 14.8	5.00 / 8.2			0.01 / 0.02
Doyan	3,300			4.98 / 16.4	5.08 / 16.8			0.004 / 0.01
Joe Mann*	1,430	0.04 / 0.06	0.15 / 0.21	2.86 / 4.1	1.28 / 1.8			0.02 / 0.03
Kiena*	1,430			4.30 / 6.1	1.62 / 2.3			0.01 / 0.01
Laronde	2,200		2.00 / 4.4	4.80 / 10.6	8.80 / 19.4	0.09 / 0.20	1.16 / 2.5	0.11 / 0.25
Norlartic*	1,100	0.06 / 1.1	0.34 / 0.37	1.00 / 1.1	0.64 / 0.70			0.01 / 0.01
Sigma	1.760			2.51 / 4.4	0.52 / 0.92		0.04 / 0.06	0.03 / 0.06
Silidor*	1,705			2.00 / 3.4	2.60 / 4.4		0.06 / 0.99	
Hope Brook	3,300			1.50 / 4.9	1.60 / 5.3		0.90 / 3.0	

* Ores treated off site

Table A.2.4: Reagent consumption in 1993 at selected Canadian gold mine/mill sites not using cyanide, in pounds per ton of ore milled, and thousands of pounds per day

Gold Mill no cyanidation	STPD Ore Milled	Frother	Collector	Lime	Cyanide	pH Modifier	Activator	Flocculant/ Coagulant
Blackdome	220	0.11 / 0.03	0.18 / 0.04					
Johnny Mountain	400	0.02 / 0.007	0.18 / 0.07					
Snip	360	0.09 / 0.03	0.02 / 0.006					0.001 / 0.0003
Tom	200	0.11 / 0.02	0.18 / 0.04					
Ptarmigan	200	0.11 / 0.02	0.18 / 0.04					
Chimo	570	0.02 / 0.01	0.16 / 0.09					0.07 / 0.04
Beliveau	990	0.02 / 0.02	0.16 / 0.15					0.07 / 0.07

Appendix 3: Flowsheets for Effluent Treatment Technology Trains

all flowsheets after Kilborn, 1991

Figure A.3.1: Typical flowsheet for Inco SO_2 - Air / Tailings Pond / Polishing pond technology train for the treatment of gold mill effluents

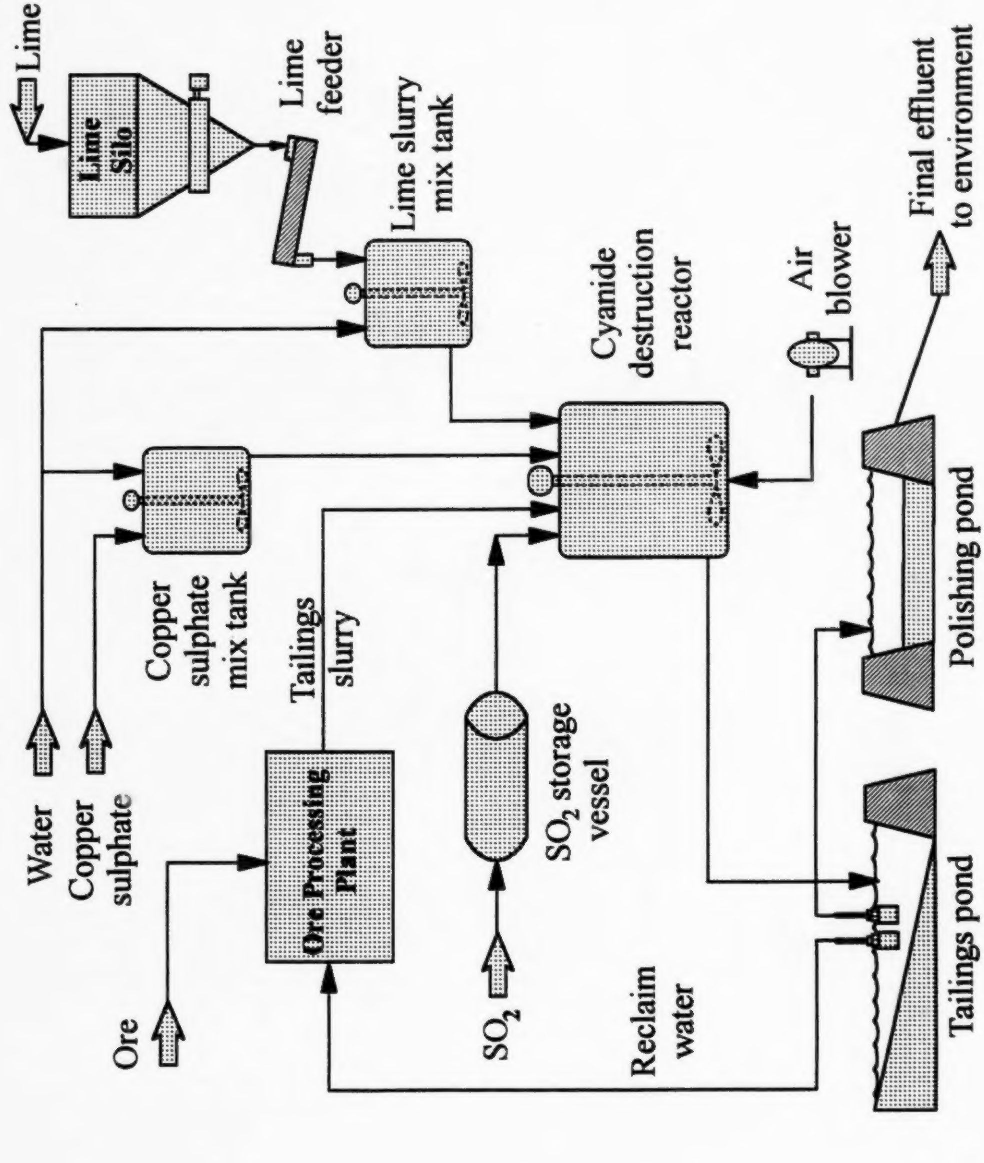

Lime
Lime Silo
Lime feeder
Lime slurry mix tank
Cyanide destruction reactor
Air blower
Final effluent to environment
Water
Copper sulphate
Copper sulphate mix tank
Tailings slurry
Ore
Ore Processing Plant
SO_2
SO_2 storage vessel
Reclaim water
Tailings pond
Polishing pond

Figure A.3.2: Typical flowsheet for Natural degradation / Inco SO_2 - Air / Polishing pond technology train for the treatment of gold mill effluents

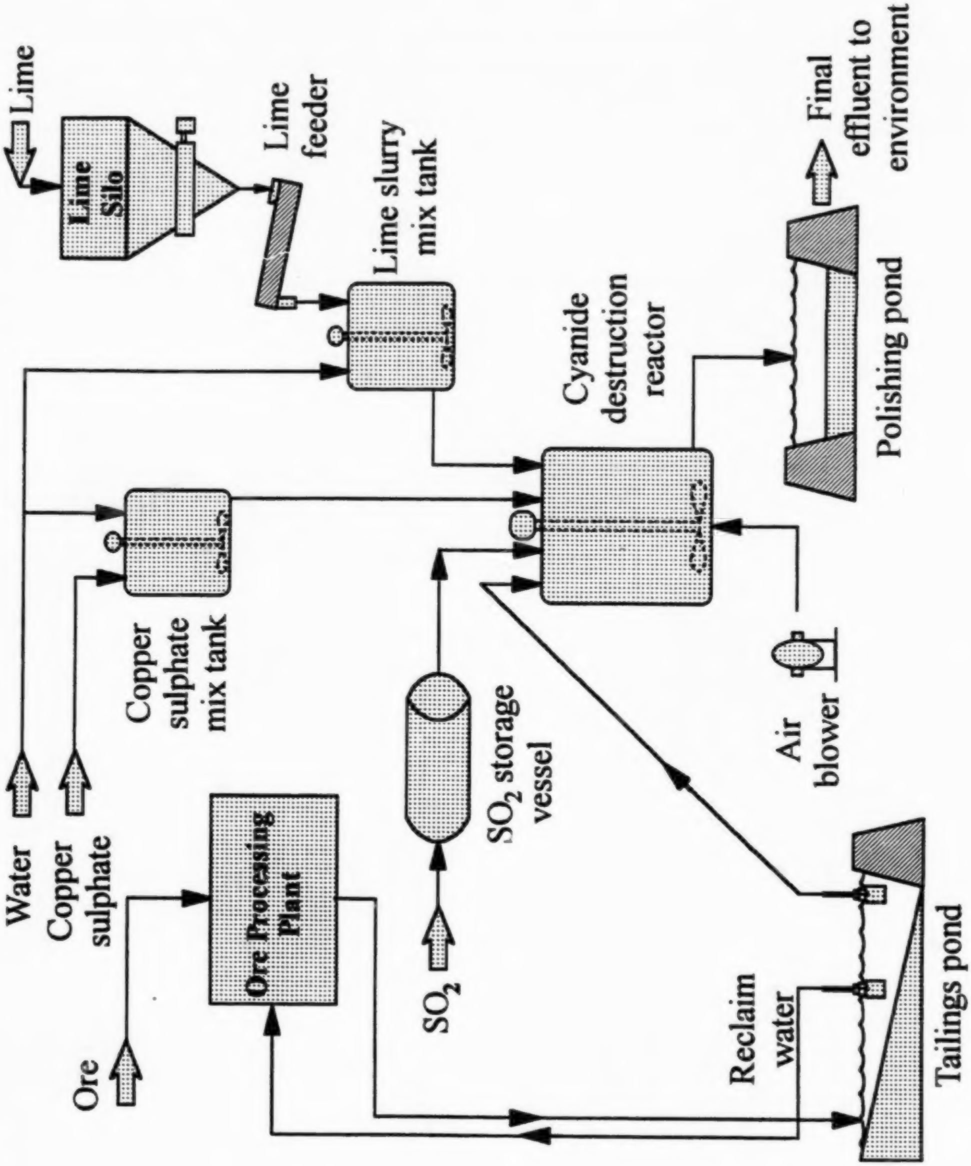

Lime
Lime Silo
Lime feeder
Lime slurry mix tank
Cyanide destruction reactor
Final effluent to environment
Polishing pond
Water
Copper sulphate
Copper sulphate mix tank
SO2 storage vessel
Air blower
Ore
Ore Processing Plant
SO2
Reclaim water
Tailings pond

Figure A.3.3: Typical flowsheet for Natural degradation / Hydrogen peroxide / Polishing pond technology train for the treatment of gold mill effluents

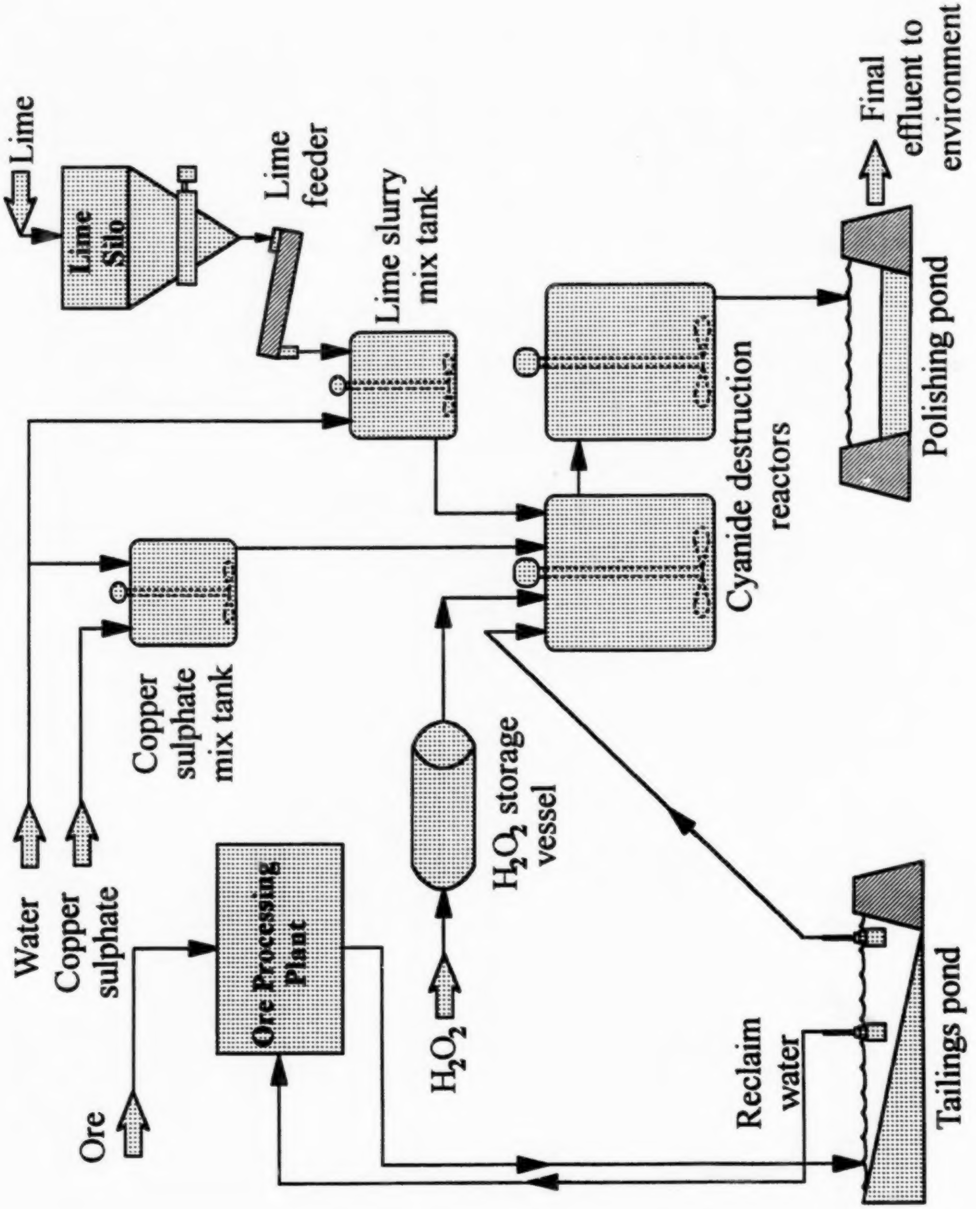

Lime
Lime Silo
Lime feeder
Lime slurry mix tank
Water
Copper sulphate
Copper sulphate mix tank
Ore
Ore Processing Plant
H_2O_2
H_2O_2 storage vessel
Cyanide destruction reactors
Final effluent to environment
Polishing pond
Reclaim water
Tailings pond

Figure A.3.4: Typical flowsheet for Natural degradation / Inco SO_2 - Air / Clarification technology train for the treatment of gold mill effluents

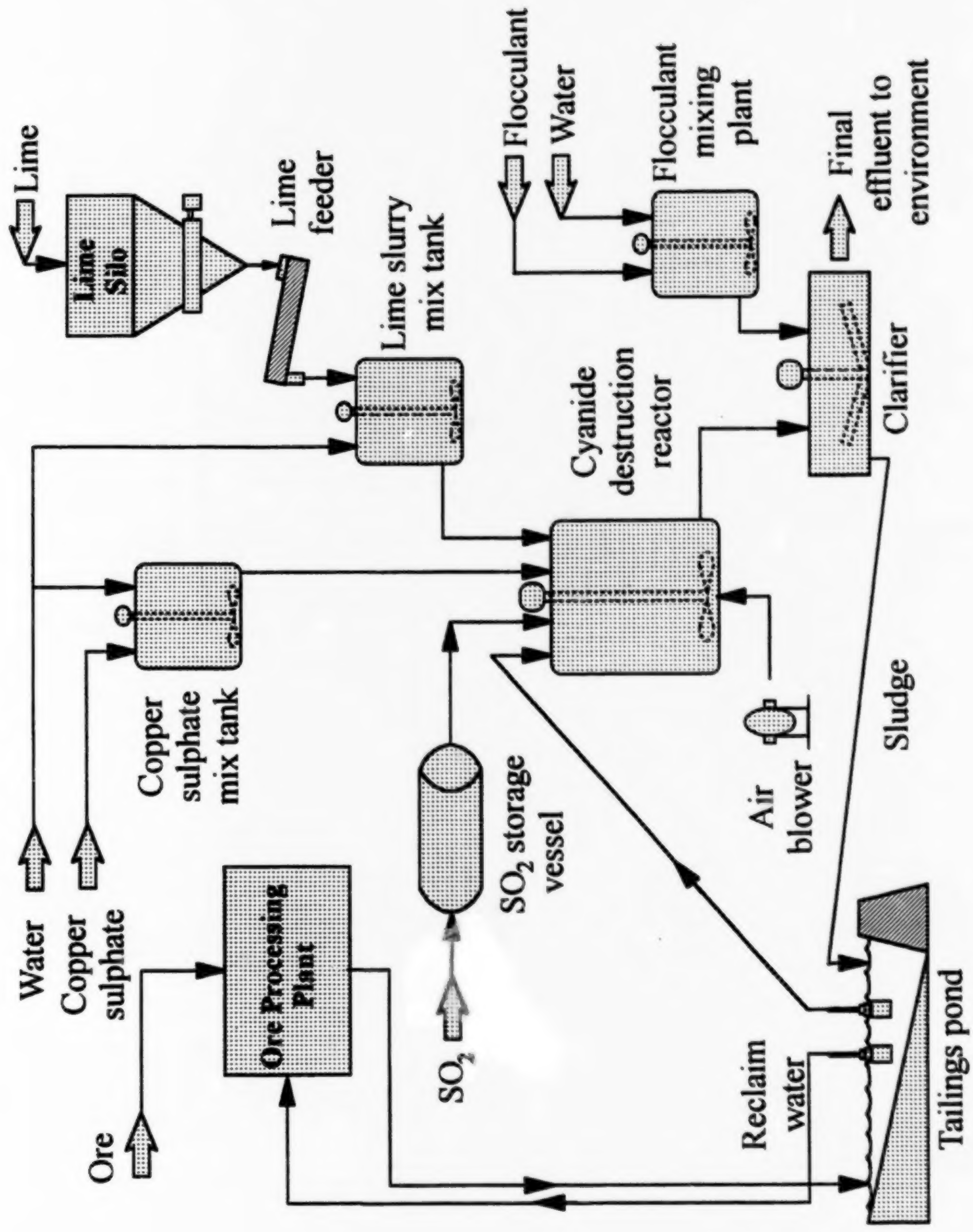

Lime
Lime Silo
Lime feeder
Lime slurry mix tank
Flocculant
Water
Flocculant mixing plant
Final effluent to environment
Cyanide destruction reactor
Clarifier
Water
Copper sulphate
Copper sulphate mix tank
Ore
Ore Processing Plant
SO_2
SO_2 storage vessel
Air blower
Sludge
Reclaim water
Tailings pond

Figure A.3.5: Typical flowsheet for Natural degradation / Hydrogen peroxide / Clarification technology train for the treatment of gold mill effluents

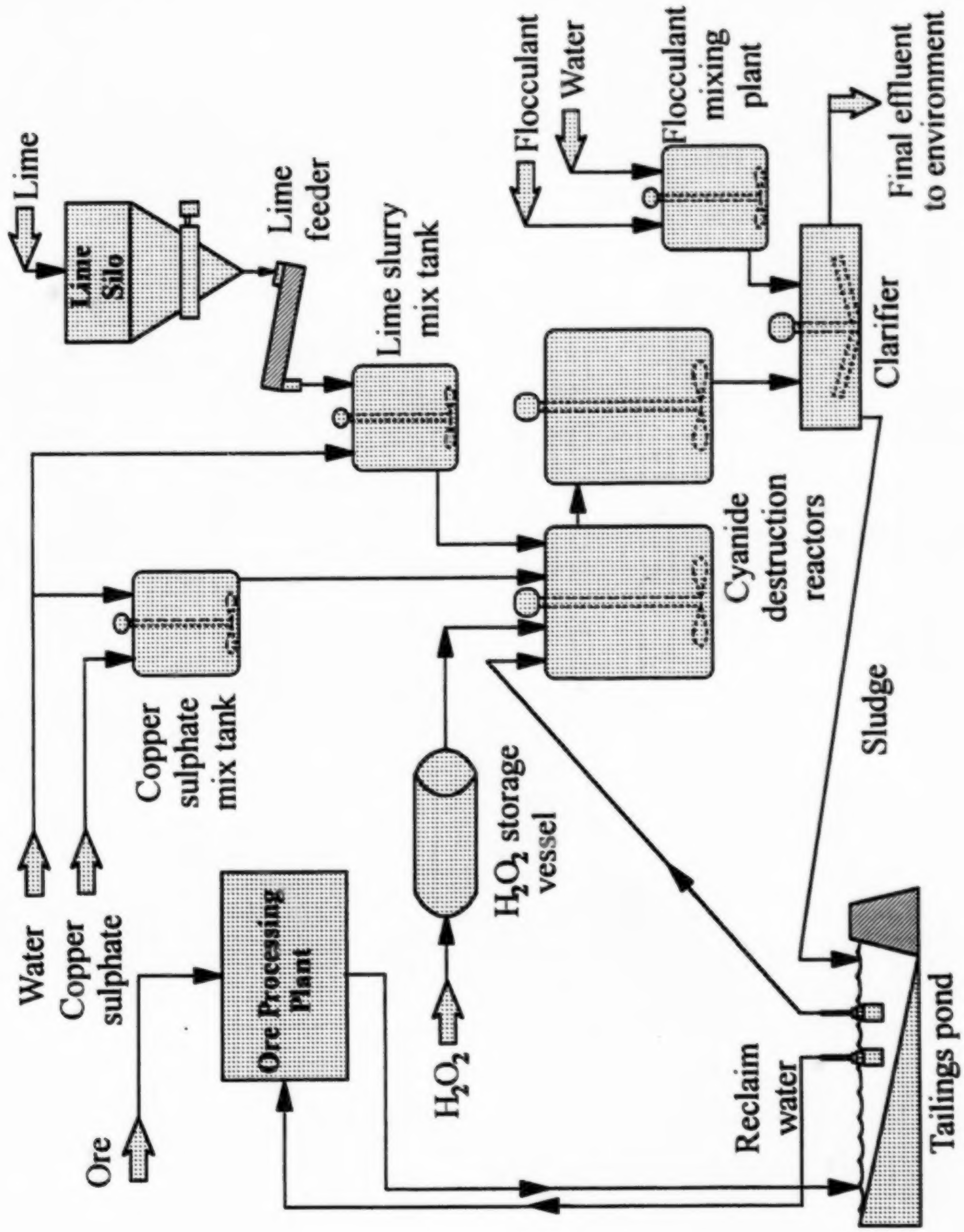

Lime
Lime Silo
Lime feeder
Lime slurry mix tank
Flocculant
Water
Flocculant mixing plant
Final effluent to environment
Clarifier
Cyanide destruction reactors
Copper sulphate mix tank
H_2O_2 storage vessel
Sludge
Water
Copper sulphate
Ore Processing Plant
H_2O_2
Reclaim water
Ore
Tailings pond

Figure A.3.6: Typical flowsheet for Tailings pond / Hydroxide precipitation / Polishing pond technology train for treatment of base metal mill effluents

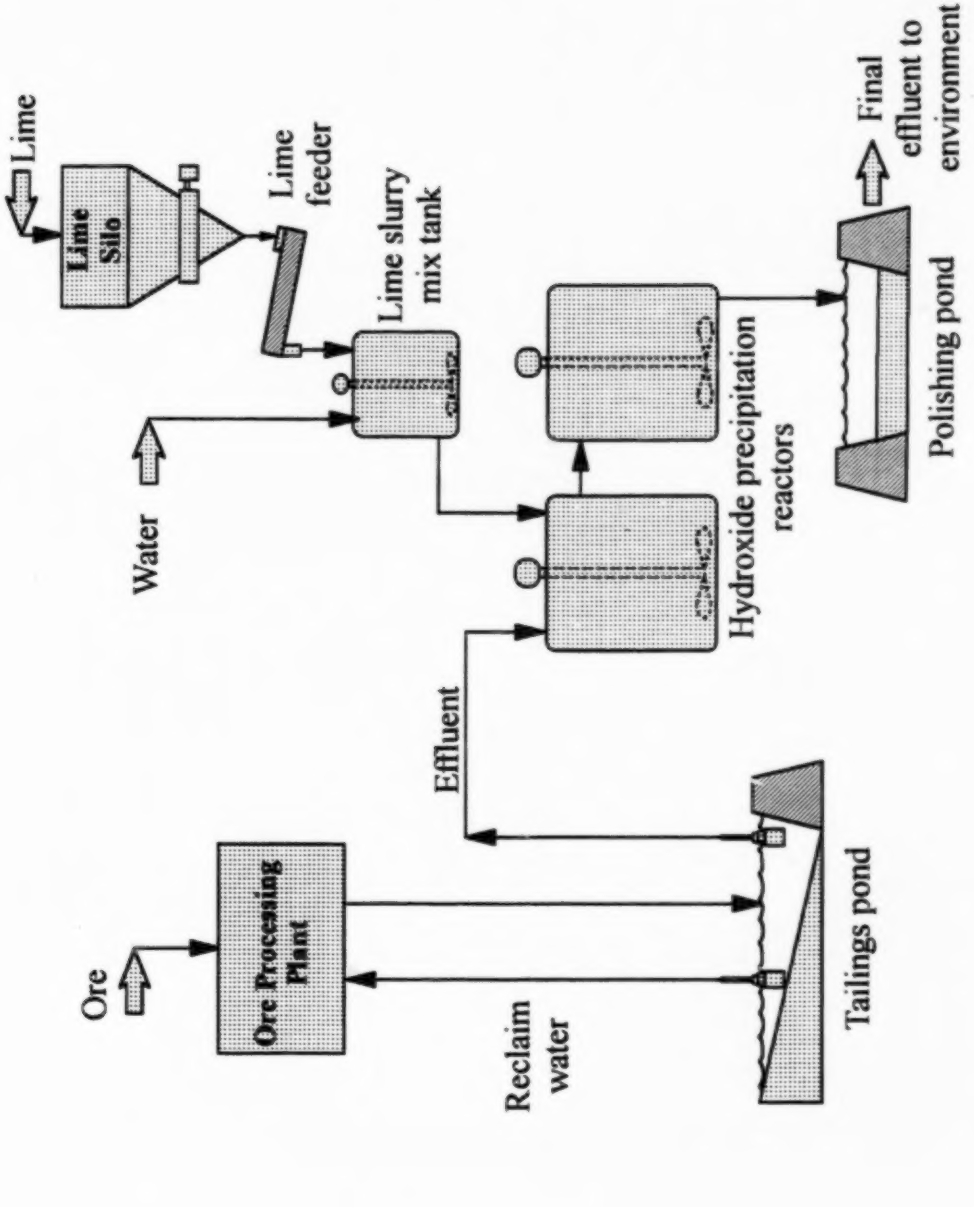

Lime
Lime Silo
Lime feeder
Lime slurry mix tank
Water
Hydroxide precipitation reactors
Final effluent to environment
Polishing pond
Effluent
Ore
Ore Processing Plant
Reclaim water
Tailings pond

Figure A.3.7: Typical flowsheet for Acid mine water pond / Hydroxide precipitation / Clarification technology train for treatment of acidic effluents

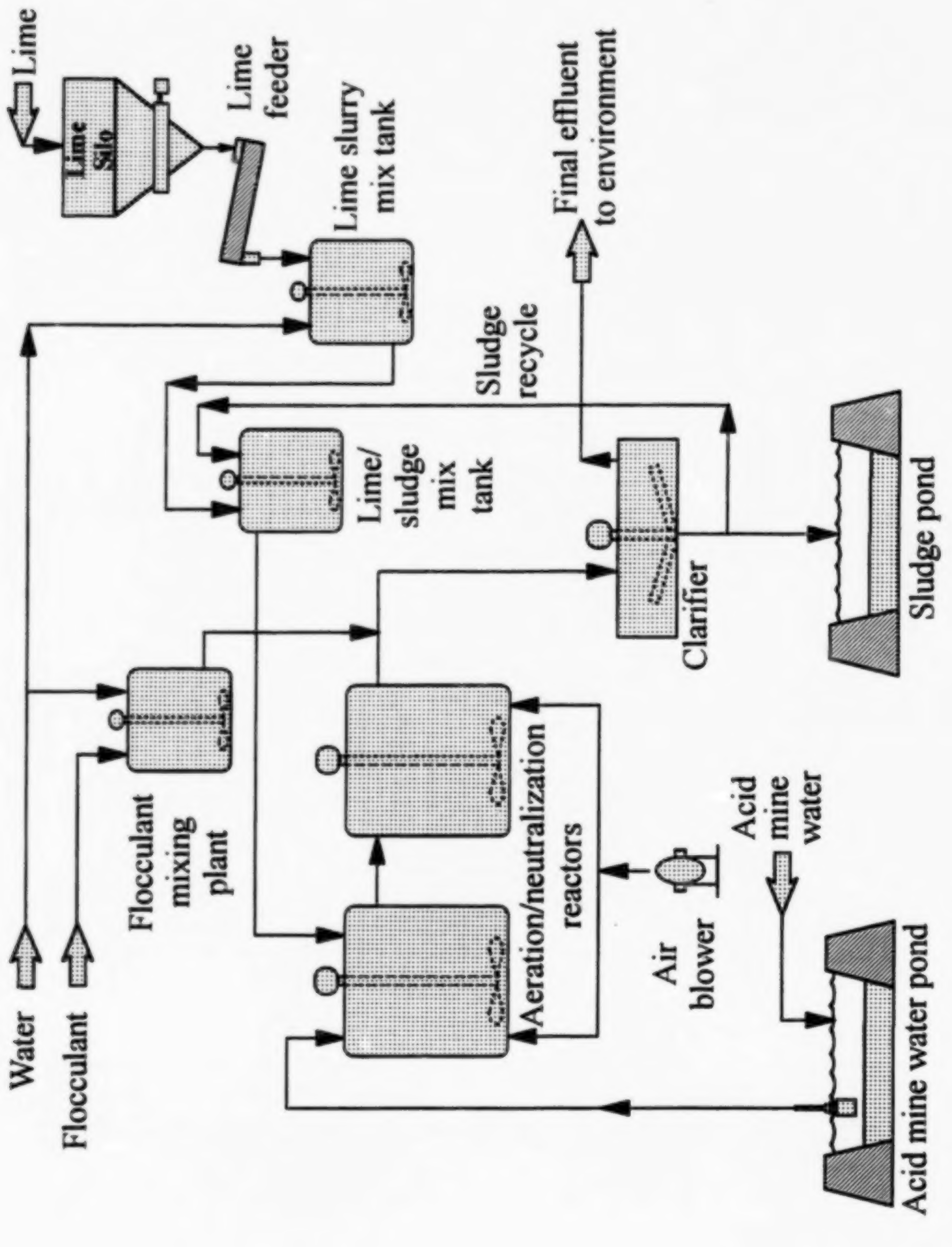

Lime
Lime Silo
Lime feeder
Lime slurry mix tank
Final effluent to environment
Sludge recycle
Lime/ sludge mix tank
Clarifier
Sludge pond
Water
Flocculant
Flocculant mixing plant
Aeration/neutralization reactors
Air blower
Acid mine water
Acid mine water pond

Figure A.3.8: Typical flowsheet for Tailings pond / Sulphide precipitation / Clarification technology train for treatment of base metal mill effluents

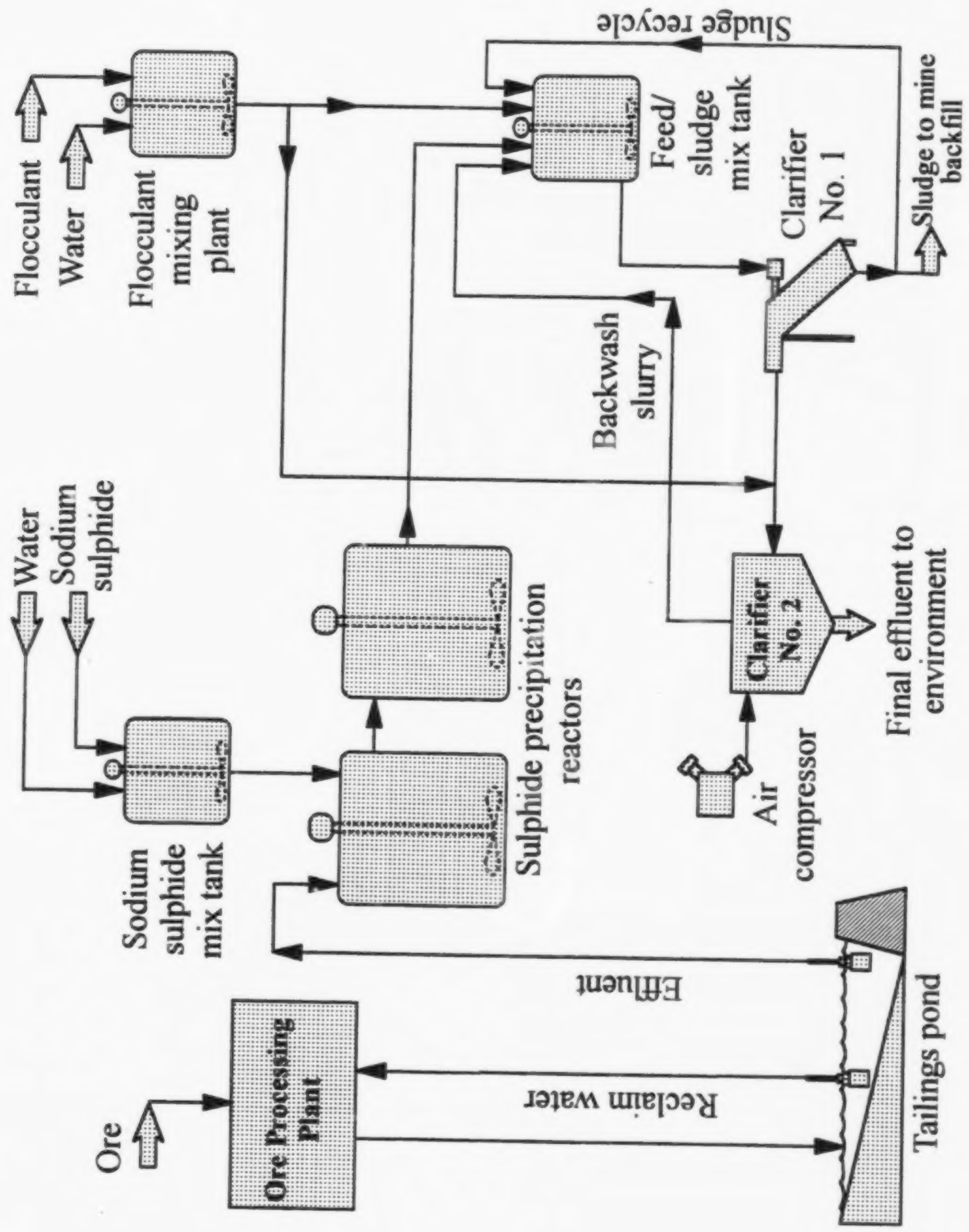
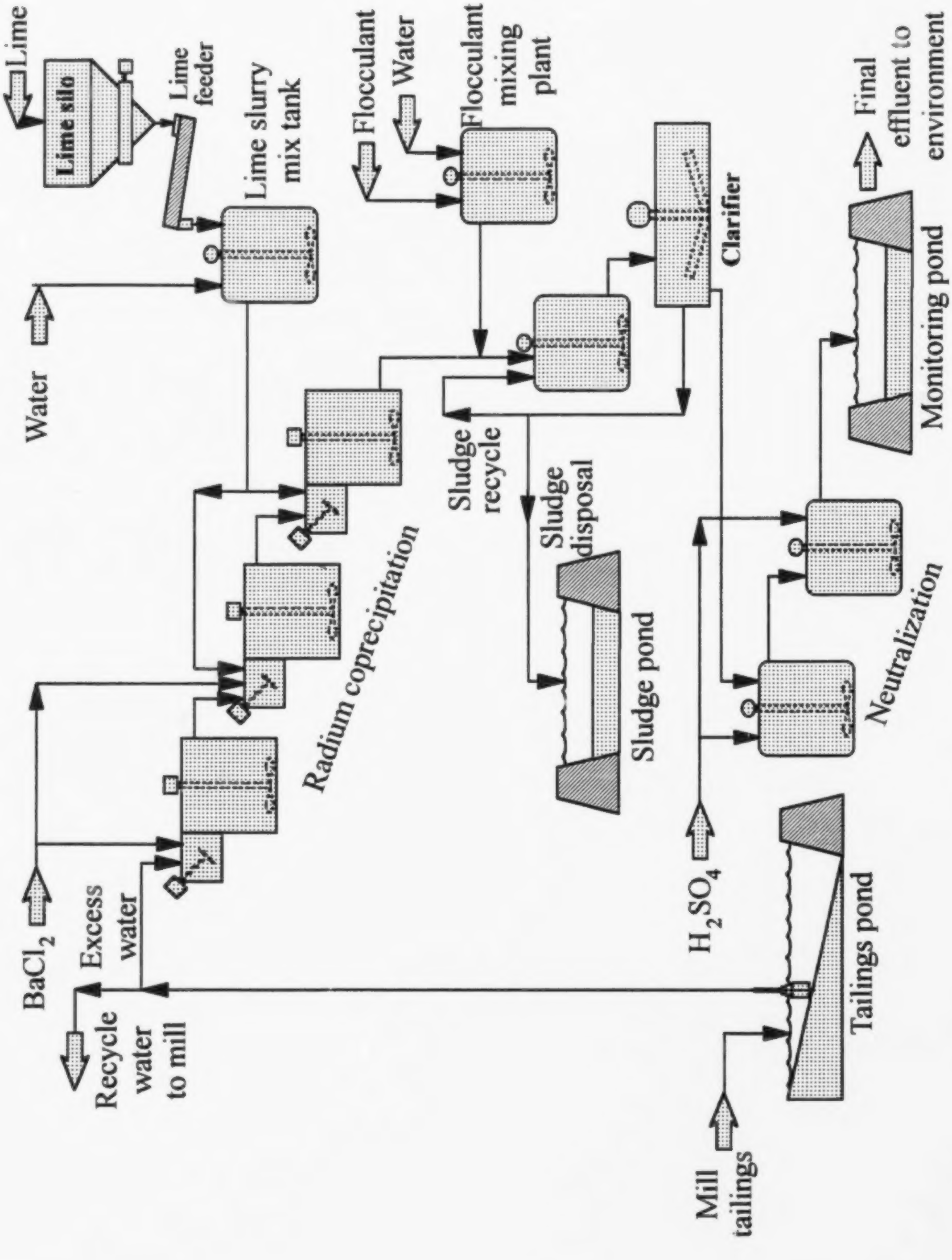

Ore
Ore Processing Plant
Reclaim water
Effluent
Tailings pond
Sodium sulphide mix tank
Water
Sodium sulphide
Sulphide precipitation reactors
Air compressor
Clarifier No. 2
Final effluent to environment
Backwash slurry
Flocculant
Water
Flocculant mixing plant
Feed/ sludge mix tank
Clarifier No. 1
Sludge to mine backfill
Sludge recycle

Figure A.3.9: Typical flowsheet for Uranium mill effluent treatment process


Lime
Lime silo
Lime feeder
Lime slurry mix tank
Water
Flocculant
Water
Flocculant mixing plant
Clarifier
Final effluent to environment
Monitoring pond
Sludge recycle
Sludge disposal
Sludge pond
Radium coprecipitation
Neutralization
BaCl$_2$
Excess water
Recycle water to mill
H$_2$SO$_4$
Tailings pond
Mill tailings